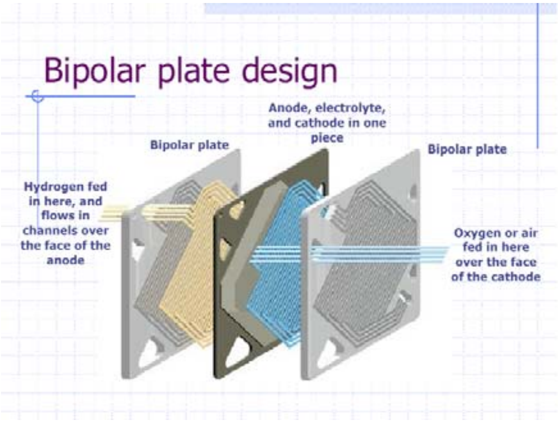
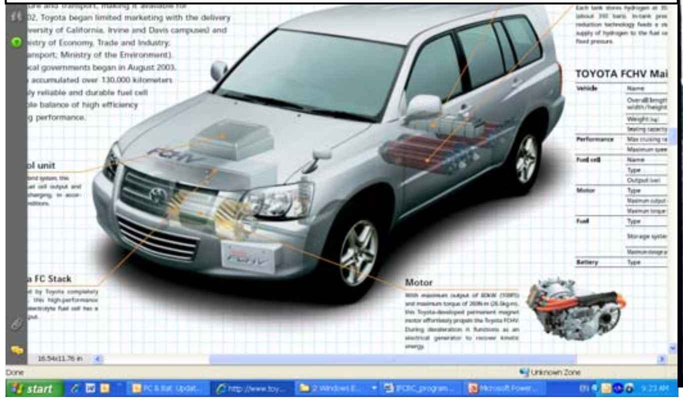
Fuel-Cell-Hybrid Vehicle (FCHV)

IFCBC, February 2009

E. Peled, Tel Aviv University



Toyota FCHV



Outline

- The oil import problem.
- The solution: renewable energy and alternative fuels (hydrogen, alcohols).
- Hydrogen production, distribution and storage
- Higher energy-conversion efficiency and greener technology with the use of fuel cells (FC).
- Development efforts (car industry)
- FCHV safety issues
- FCHV niche market.
- PEM FC cost analysis.
- Market penetration of FCHVs

The Impact of Fuel Cells

Fuel Cells could have a great positive effect on Western society

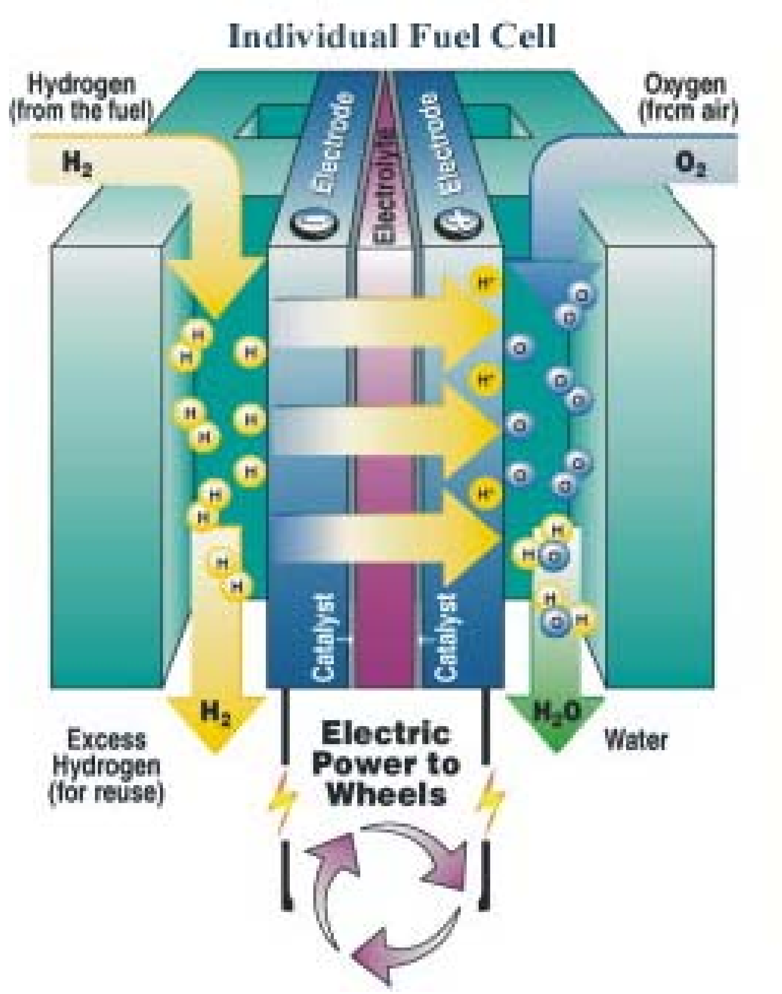
They would reduce

- Dependence on oil import
- Pollution

Disadvantages

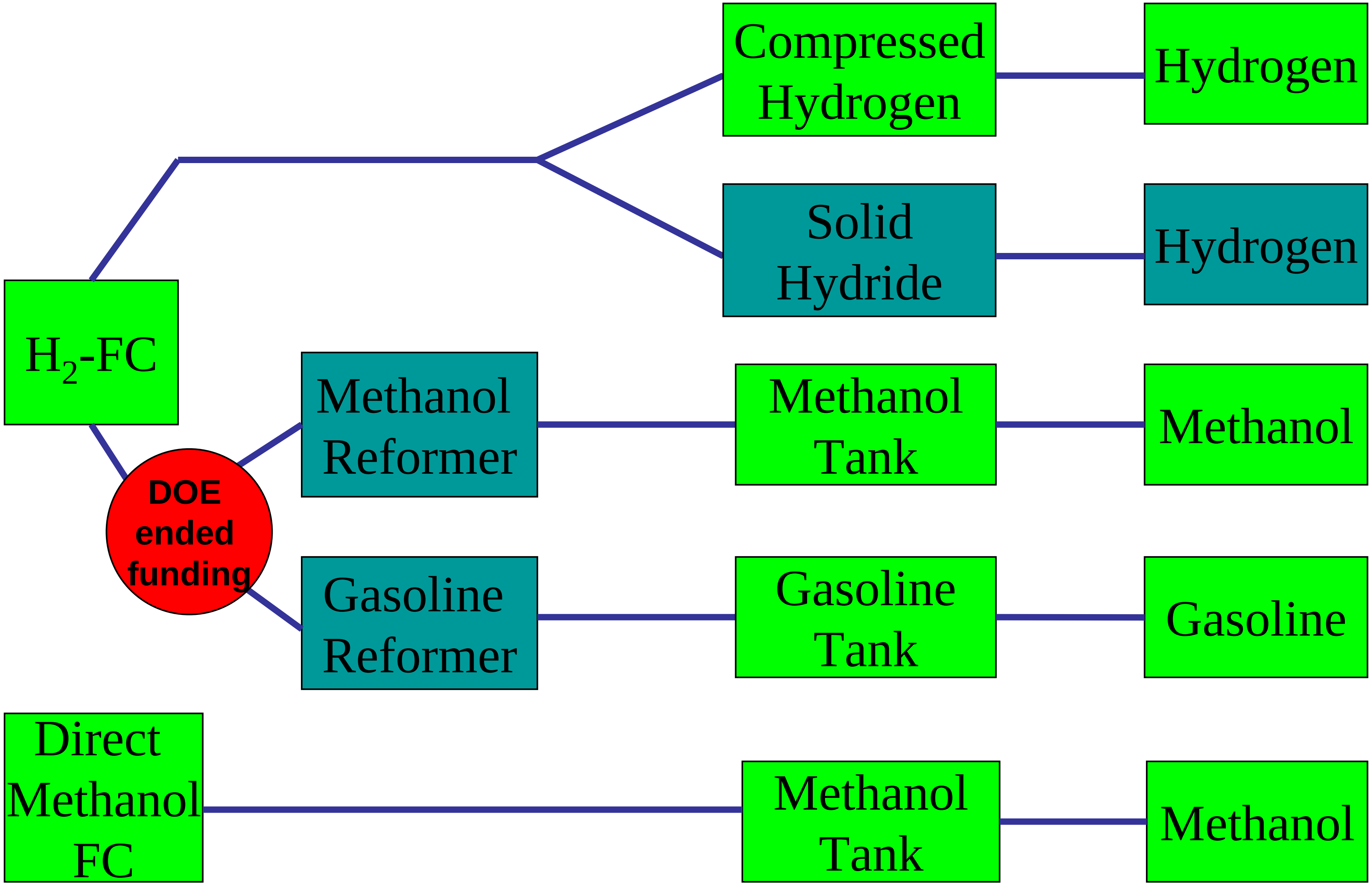
- Currently cost prohibitive
- Require a new hydrogen infrastructure

Basic Operation of a PEM Fuel Cell



- **Chemical Reaction Produces Electricity**
- **Fuel - H_2, O_2**
- **By-Product - H_2O**
- **Electrons Released at Anode**
- **Electrons Collected at Cathode**

Possible EV System Configurations: which is the best?



H_2-FC

Compressed Hydrogen

Hydrogen

Solid Hydride

Hydrogen

DOE ended funding

Methanol Reformer

Methanol Tank

Methanol

Gasoline Reformer

Gasoline Tank

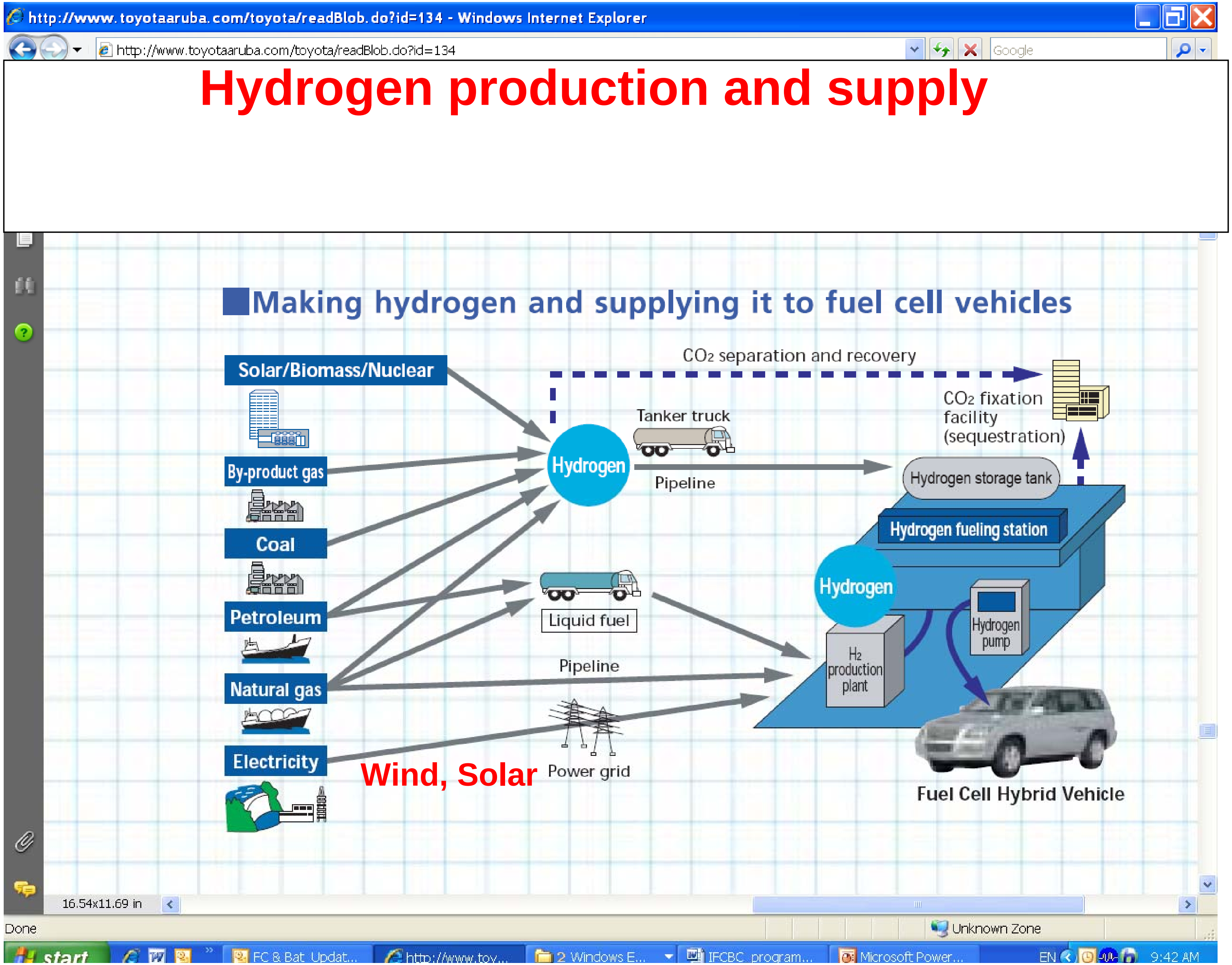
Gasoline

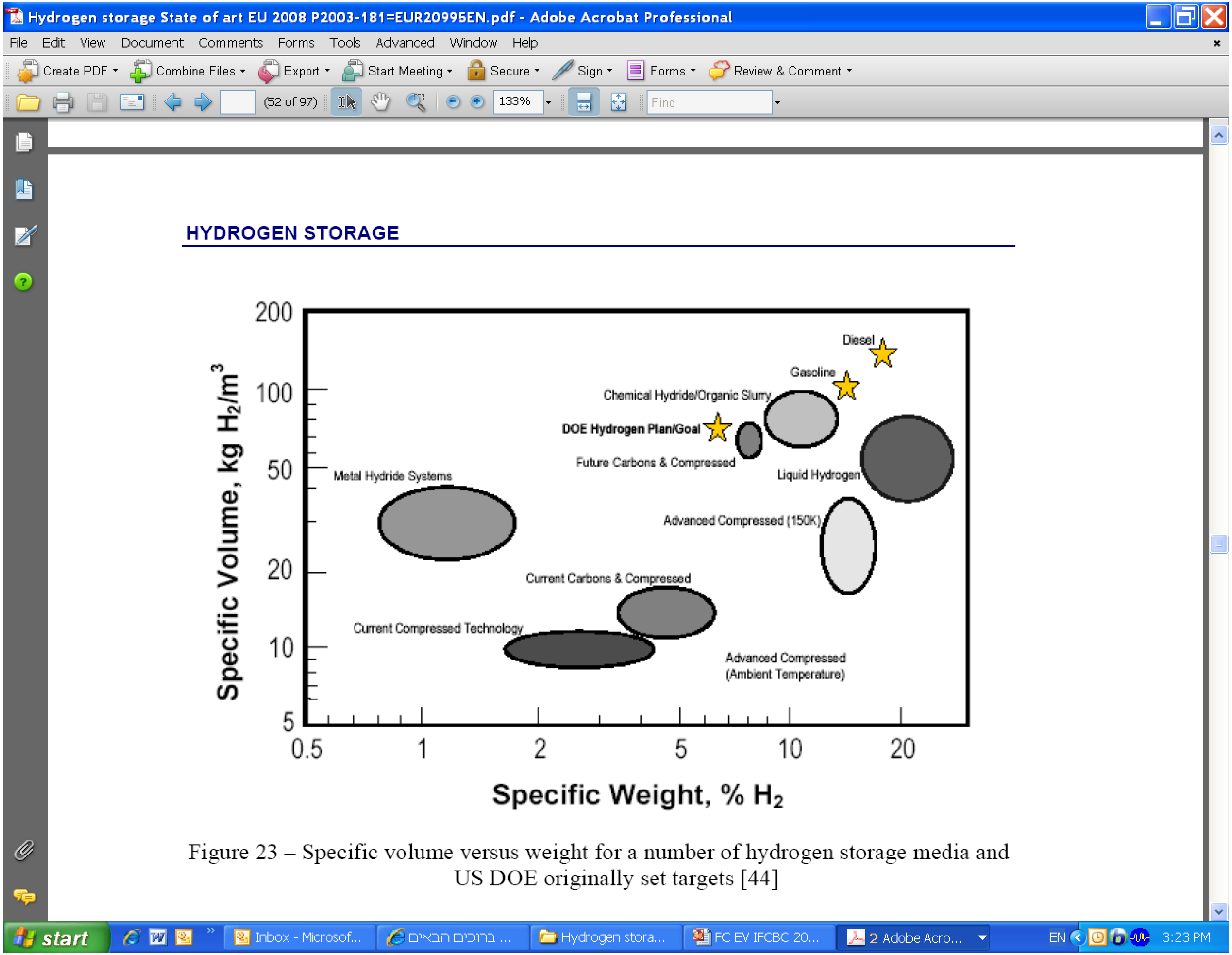
Direct Methanol FC

Methanol Tank

Methanol

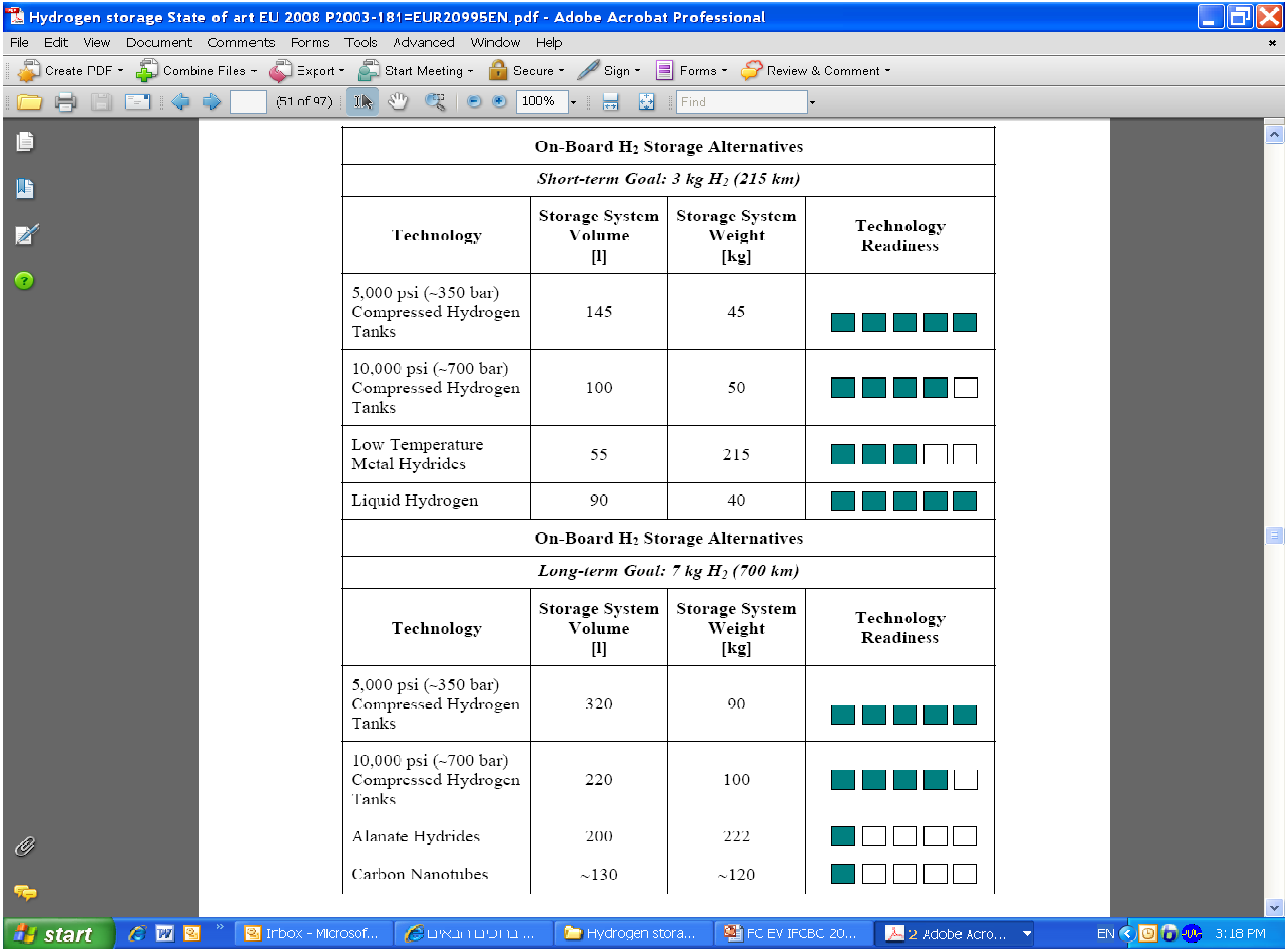
Hydrogen production and supply





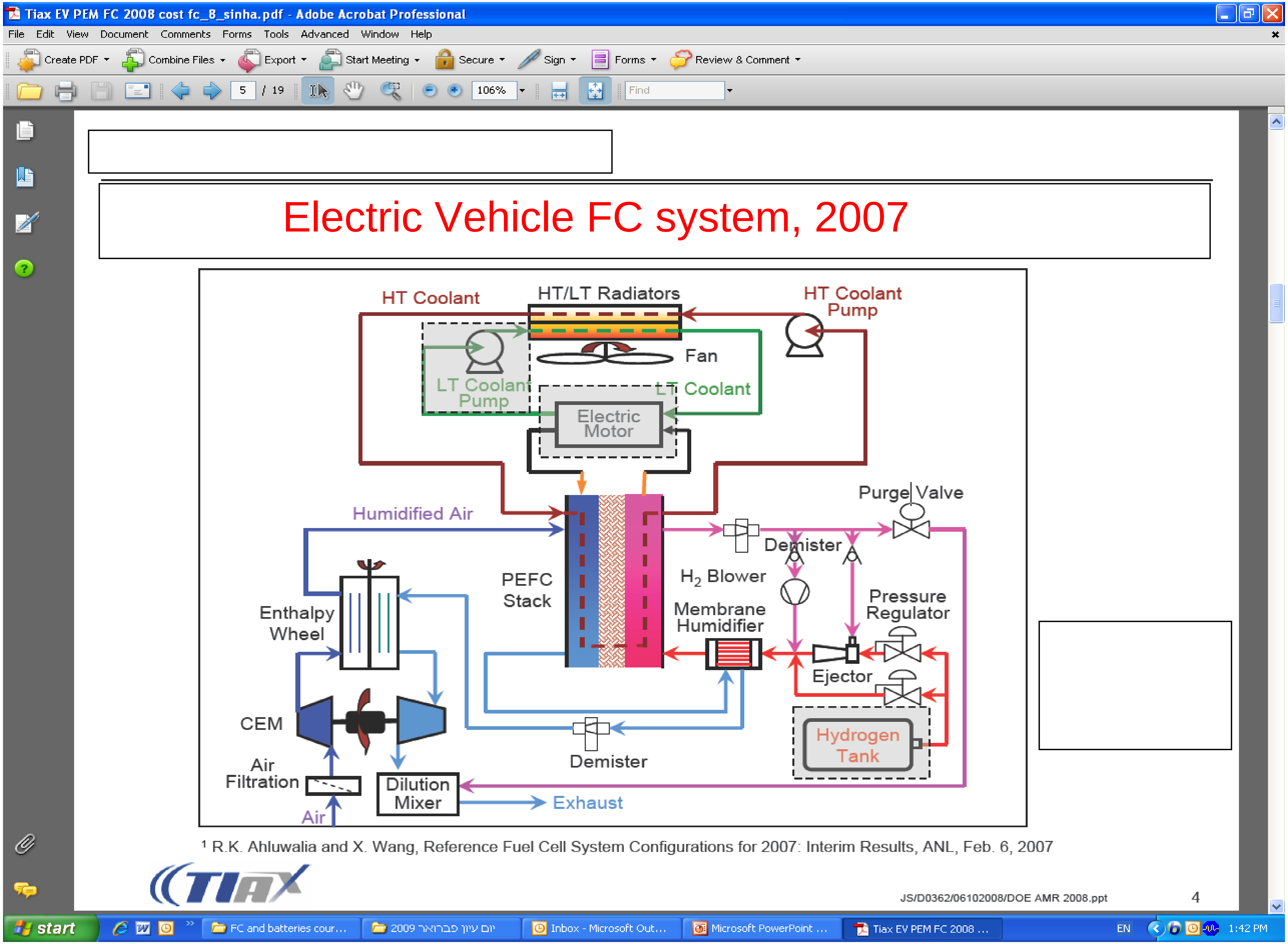
HYDROGEN STORAGE

Figure 23 – Specific volume versus weight for a number of hydrogen storage media and US DOE originally set targets [44]



On-Board H_2 Storage Alternatives			
Short-term Goal: 3 kg H_2 (215 km)			
Technology	**Storage System Volume [l]**	**Storage System Weight [kg]**	**Technology Readiness**
5,000 psi (~350 bar) Compressed Hydrogen Tanks	145	45	■■■■■
10,000 psi (~700 bar) Compressed Hydrogen Tanks	100	50	■■■■□
Low Temperature Metal Hydrides	55	215	■■■□□
Liquid Hydrogen	90	40	■■■■■

On-Board H_2 Storage Alternatives			
Long-term Goal: 7 kg H_2 (700 km)			
Technology	**Storage System Volume [l]**	**Storage System Weight [kg]**	**Technology Readiness**
5,000 psi (~350 bar) Compressed Hydrogen Tanks	320	90	■■■■■
10,000 psi (~700 bar) Compressed Hydrogen Tanks	220	100	■■■■□
Alanate Hydrides	200	222	■□□□□
Carbon Nanotubes	~130	~120	■□□□□

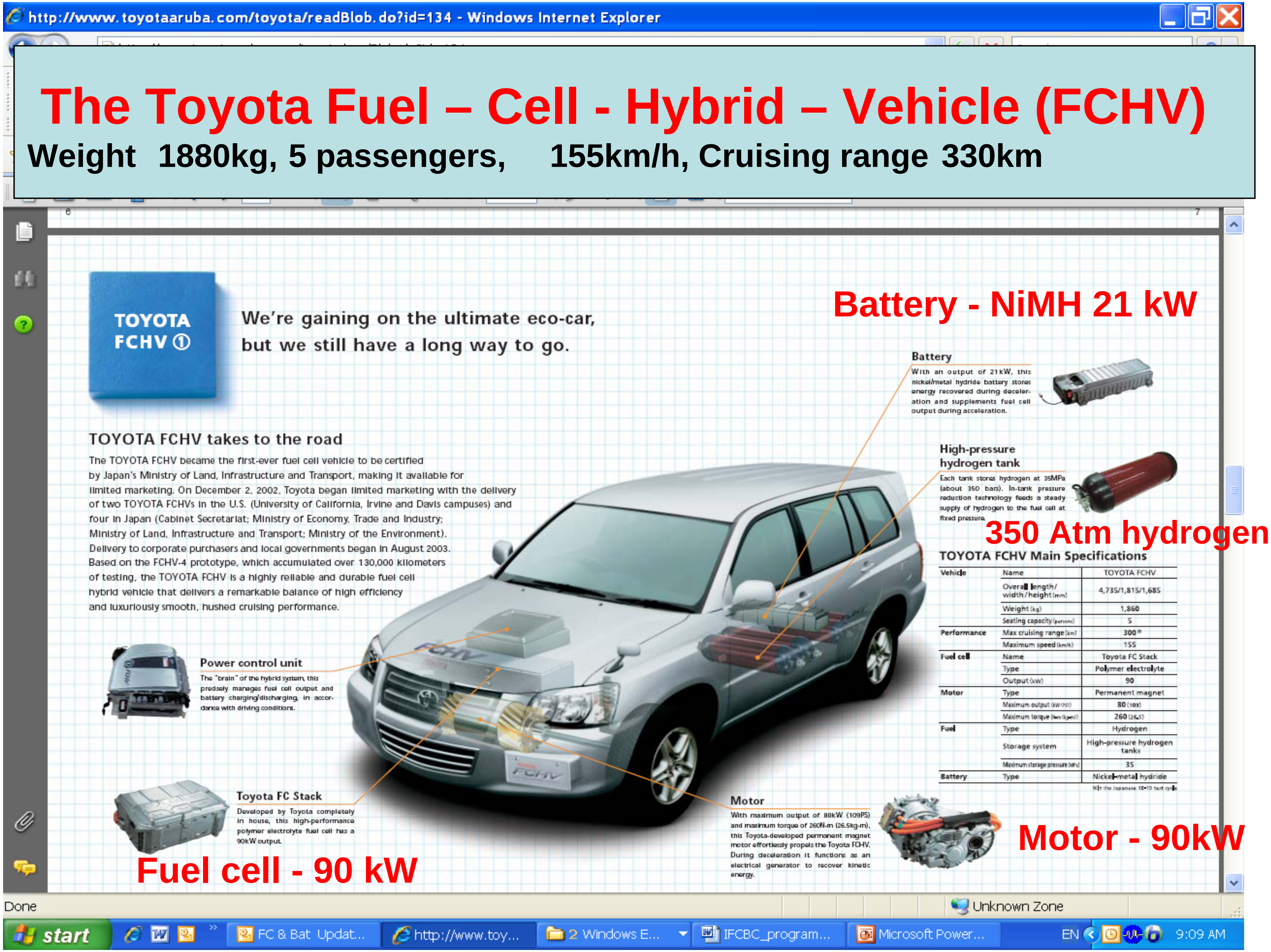


Electric Vehicle FC system, 2007

[1] R.K. Ahluwalia and X. Wang, Reference Fuel Cell System Configurations for 2007: Interim Results, ANL, Feb. 6, 2007

The Toyota Fuel – Cell - Hybrid – Vehicle (FCHV)

Weight 1880kg, 5 passengers, 155km/h, Cruising range 330km



We're gaining on the ultimate eco-car, but we still have a long way to go.

TOYOTA FCHV takes to the road

The TOYOTA FCHV became the first-ever fuel cell vehicle to be certified by Japan's Ministry of Land, Infrastructure and Transport, making it available for limited marketing. On December 2, 2002, Toyota began limited marketing with the delivery of two TOYOTA FCHVs in the U.S. (University of California, Irvine and Davis campuses) and four in Japan (Cabinet Secretariat; Ministry of Economy, Trade and Industry; Ministry of Land, Infrastructure and Transport; Ministry of the Environment). Delivery to corporate purchasers and local governments began in August 2003. Based on the FCHV-4 prototype, which accumulated over 130,000 kilometers of testing, the TOYOTA FCHV is a highly reliable and durable fuel cell hybrid vehicle that delivers a remarkable balance of high efficiency and luxuriously smooth, hushed cruising performance.

Power control unit

The "brain" of the hybrid system, this precisely manages fuel cell output and battery charging/discharging, in accordance with driving conditions.

Toyota FC Stack

Developed by Toyota completely in house, this high-performance polymer electrolyte fuel cell has a 90kW output.

Fuel cell - 90 kW

Battery - NiMH 21 kW

Battery

With an output of 21kW, this nickel/metal hydride battery stores energy recovered during deceleration and supplements fuel cell output during acceleration.

High-pressure hydrogen tank

Each tank stores hydrogen at 35MPa (about 350 bars). In-tank pressure reduction technology feeds a steady supply of hydrogen to the fuel cell at fixed pressure.

350 Atm hydrogen

TOYOTA FCHV Main Specifications

Vehicle	Name	TOYOTA FCHV
	Overall length/ width/height (mm)	4,735/1,815/1,685
	Weight (kg)	1,860
	Seating capacity (persons)	5
Performance	Max cruising range (km)	300※
	Maximum speed (km/h)	155
Fuel cell	Name	Toyota FC Stack
	Type	Polymer electrolyte
	Output (kW)	90
Motor	Type	Permanent magnet
	Maximum output (kW (PS))	80 (109)
	Maximum torque (N-m (kg-m))	260 (26.5)
Fuel	Type	Hydrogen
	Storage system	High-pressure hydrogen tanks
	Maximum storage pressure (MPa)	35
Battery	Type	Nickel-metal hydride

※In the Japanese 10•15 test cycle

Motor

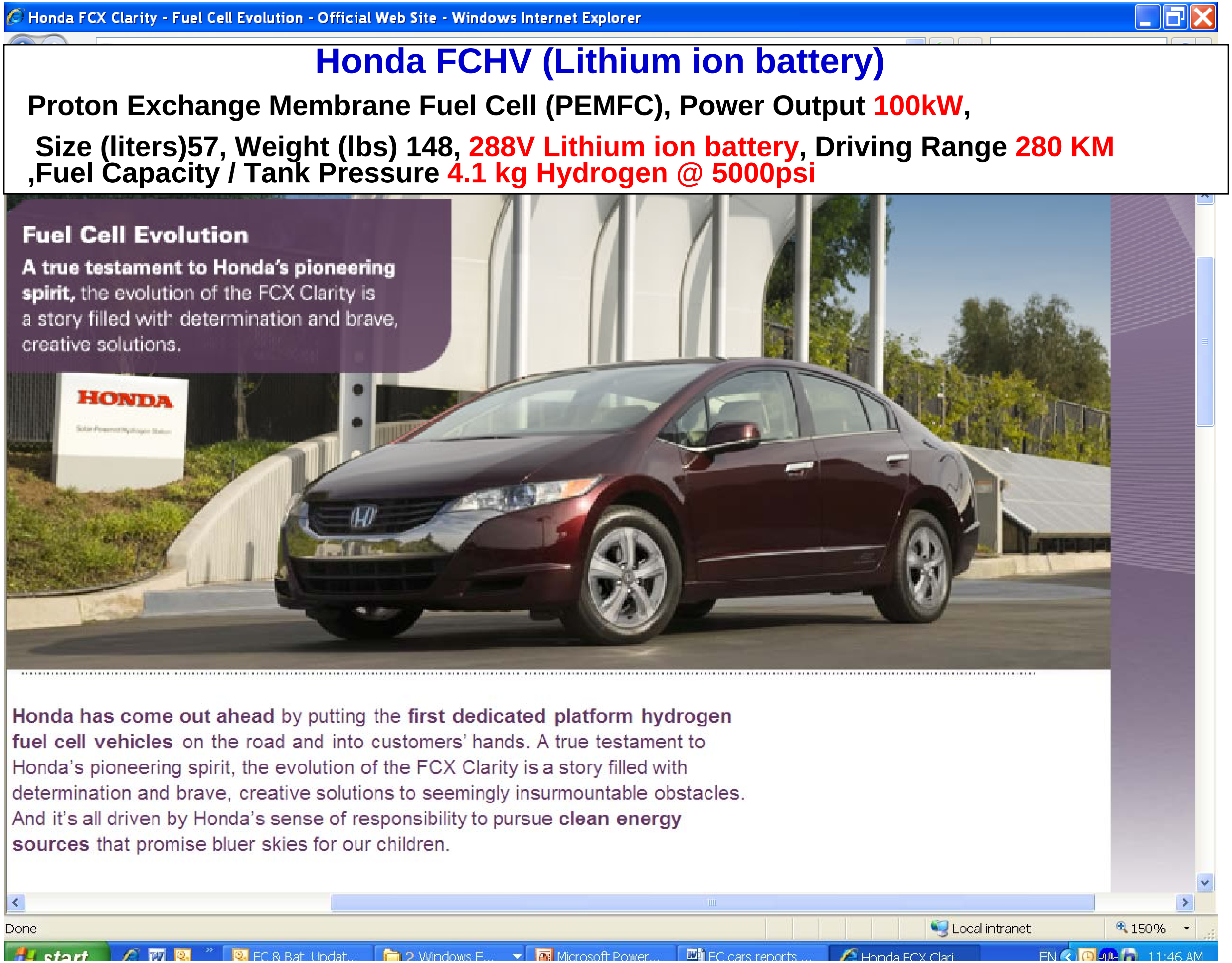
With maximum output of 80kW (109PS) and maximum torque of 260N-m (26.5kg-m), this Toyota-developed permanent magnet motor effortlessly propels the Toyota FCHV. During deceleration it functions as an electrical generator to recover kinetic energy.

Motor - 90kW

Honda FCHV (Lithium ion battery)

Proton Exchange Membrane Fuel Cell (PEMFC), Power Output 100kW,

Size (liters)57, Weight (lbs) 148, 288V Lithium ion battery, Driving Range 280 KM ,Fuel Capacity / Tank Pressure 4.1 kg Hydrogen @ 5000psi



Honda FCX Clarity - Fuel Cell Evolution - Official Web Site - Windows Internet Explorer

Fuel Cell Evolution

A true testament to Honda's pioneering spirit, the evolution of the FCX Clarity is a story filled with determination and brave, creative solutions.

Honda has come out ahead by putting the **first dedicated platform hydrogen fuel cell vehicles** on the road and into customers' hands. A true testament to Honda's pioneering spirit, the evolution of the FCX Clarity is a story filled with determination and brave, creative solutions to seemingly insurmountable obstacles. And it's all driven by Honda's sense of responsibility to pursue **clean energy sources** that promise bluer skies for our children.

Kia - new Borrego FCHV

- A 115-kW fuel cell system
- A lithium-ion battery in a hybrid-drive system (offers a zero starting capability down to -30ºC).
- Maximum speed of 100 mph
- Traveling range of 315 miles.
- The company plans to deploy a small fleet of the fuel cell Borregos on roadways during 2010.

Kia to present Borrego FCEV in L.A. - [2009 Kia Borrego] - MotorAuthority - Car news, reviews, - Windows Internet Explorer

Kia to present Borrego FCEV in L.A.

POSTED FRI NOV 14 2008 3:19 AM BY JEREMY WEBER

GM HydroGen 4 FCEV

Passed 400,000 miles of testing in the U.S. (where its known as the ChevroletEquinoxFuel Cell), capable of 0-62mph in around 12 seconds, has a top speed of 100 mph and a range of around 200 miles.

GM HydroGen4 fuel cell vehicle to begin European testing

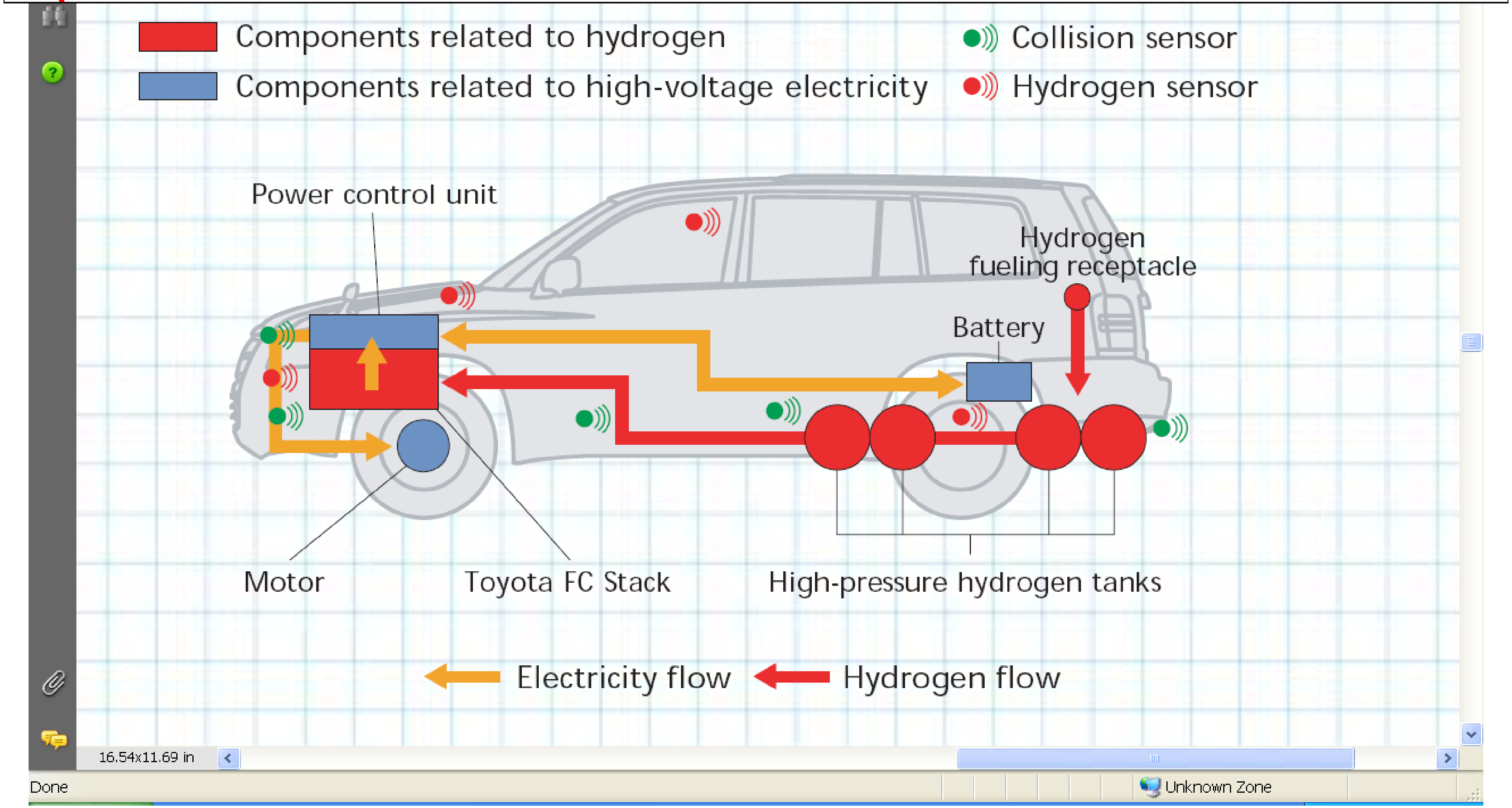
Image 1 of 7 | Next »

Mercedes' BlueZERO Hydrogen Concept

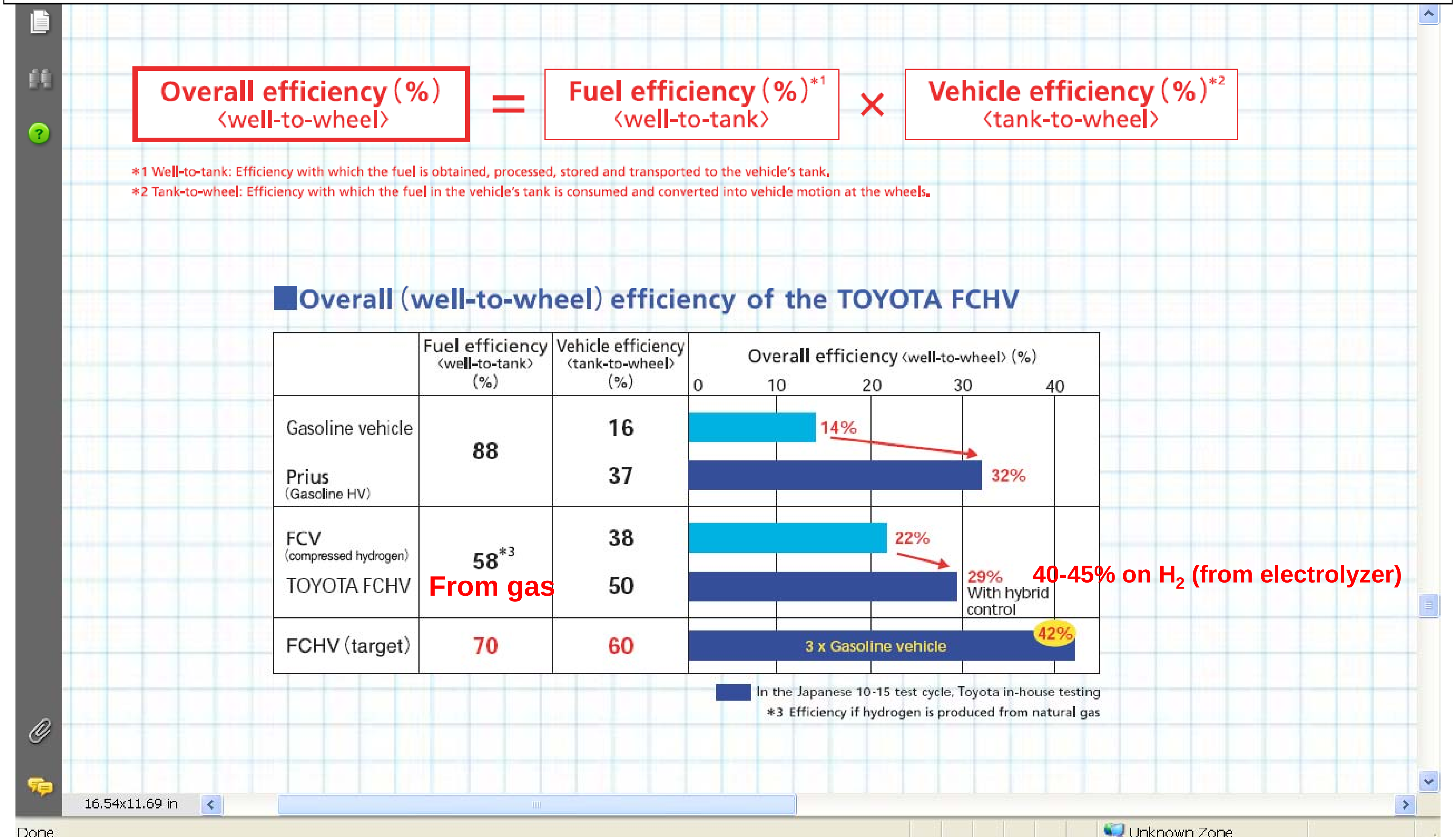
- **The BlueZERO F-CELL (fuel cell) has a range of 400 km on one tank of Hydrogen and 100 km on the 17.5-kWh lithium ion battery.**
- **It is a "concept" cars and no plans for production have been announced so far.**

Safety issues

- If a collision occurs, sensors in the TOYOTA FCHV’s front, rear and sides detect impact and instantly shut the valves on the high-pressure hydrogen tanks.
- For additional safety, the valves are also closed if leakage is detected by any of the hydrogen sensors placed at multiple locations within the vehicle,
- **The high pressure hydrogen tanks are designed for maximum safety to avoid rupture even if the vehicle suffers a rear-end collision.**



Overall efficiency of cars (well to wheel)



Overall efficiency (%) ⟨well-to-wheel⟩ = **Fuel efficiency (%)**[*1] ⟨well-to-tank⟩ × **Vehicle efficiency (%)**[*2] ⟨tank-to-wheel⟩

*1 Well-to-tank: Efficiency with which the fuel is obtained, processed, stored and transported to the vehicle's tank.
*2 Tank-to-wheel: Efficiency with which the fuel in the vehicle's tank is consumed and converted into vehicle motion at the wheels.

■Overall (well-to-wheel) efficiency of the TOYOTA FCHV

	Fuel efficiency ⟨well-to-tank⟩ (%)	Vehicle efficiency ⟨tank-to-wheel⟩ (%)	Overall efficiency ⟨well-to-wheel⟩ (%)
Gasoline vehicle	88	16	14%
Prius (Gasoline HV)		37	32%
FCV (compressed hydrogen)	58[*3]	38	22%
TOYOTA FCHV	From gas	50	29% With hybrid control
FCHV (target)	70	60	3 x Gasoline vehicle 42%

40-45% on H_2 (from electrolyzer)

■ In the Japanese 10-15 test cycle, Toyota in-house testing

*3 Efficiency if hydrogen is produced from natural gas

Niche FCHV transportation applications:

UMV and all electric airplanes

Scooters, motorbikes and bicycles (Beijing as a sample)

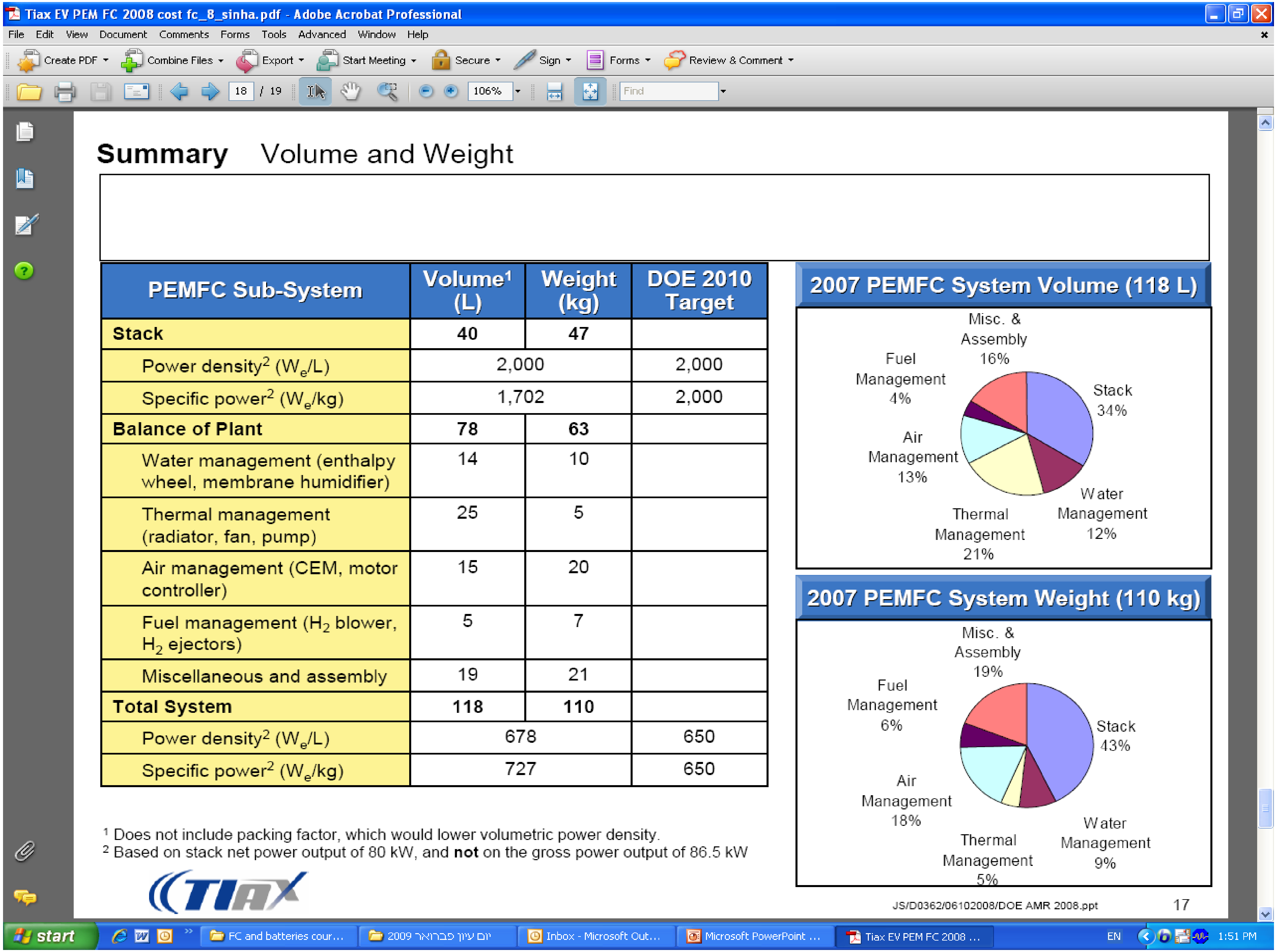
APUs

Material handling (fast charge)

Fuel cell trains

Mobility assistance vehicles

Figure 6: (left) SFC Smart Fuel Cell scooter and (right) Intelligent Energy/Suzuki Crosscage bike



Summary Volume and Weight

PEMFC Sub-System	Volume[1] (L)	Weight (kg)	DOE 2010 Target
Stack	**40**	**47**	
Power density[2] (W_e/L)	2,000		2,000
Specific power[2] (W_e/kg)	1,702		2,000
Balance of Plant	**78**	**63**	
Water management (enthalpy wheel, membrane humidifier)	14	10	
Thermal management (radiator, fan, pump)	25	5	
Air management (CEM, motor controller)	15	20	
Fuel management (H_2 blower, H_2 ejectors)	5	7	
Miscellaneous and assembly	19	21	
Total System	**118**	**110**	
Power density[2] (W_e/L)	678		650
Specific power[2] (W_e/kg)	727		650

2007 PEMFC System Volume (118 L)

2007 PEMFC System Weight (110 kg)

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[1] Does not include packing factor, which would lower volumetric power density.

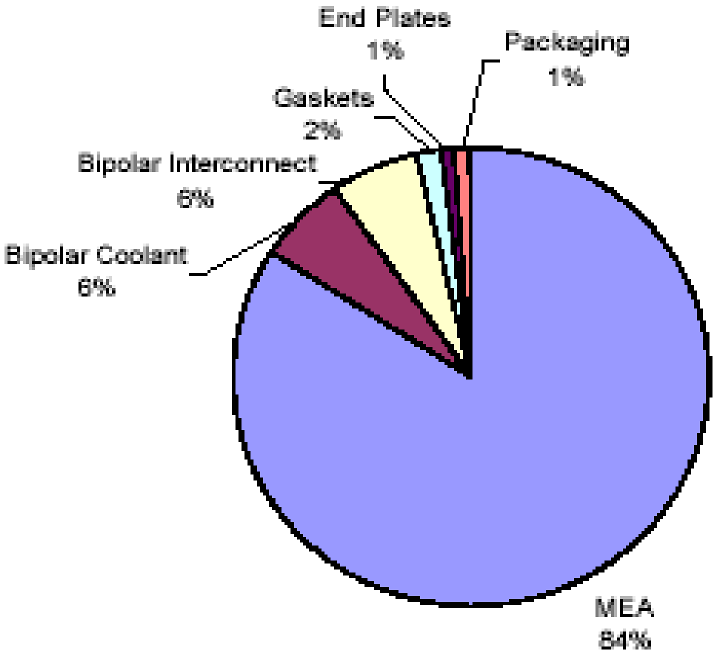
[2] Based on stack net power output of 80 kW, and **not** on the gross power output of 86.5 kW

The cost problem of PEM FC - Stack

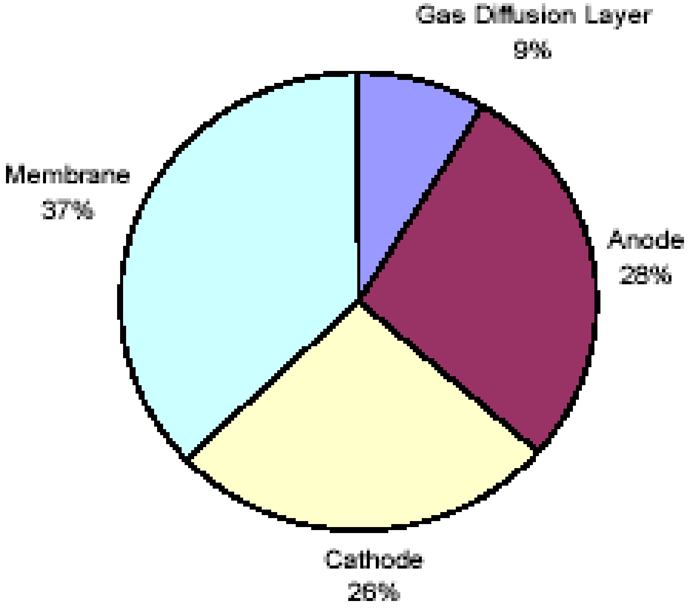
Results Baseline System *Fuel Cell Stack Cost Breakdown*

Platinum and the electrolyte membrane are the major contributors to the stack cost.

Yr 2001 Fuel Cell Stack Cost Breakdown (Stack Cost: $181/kW)



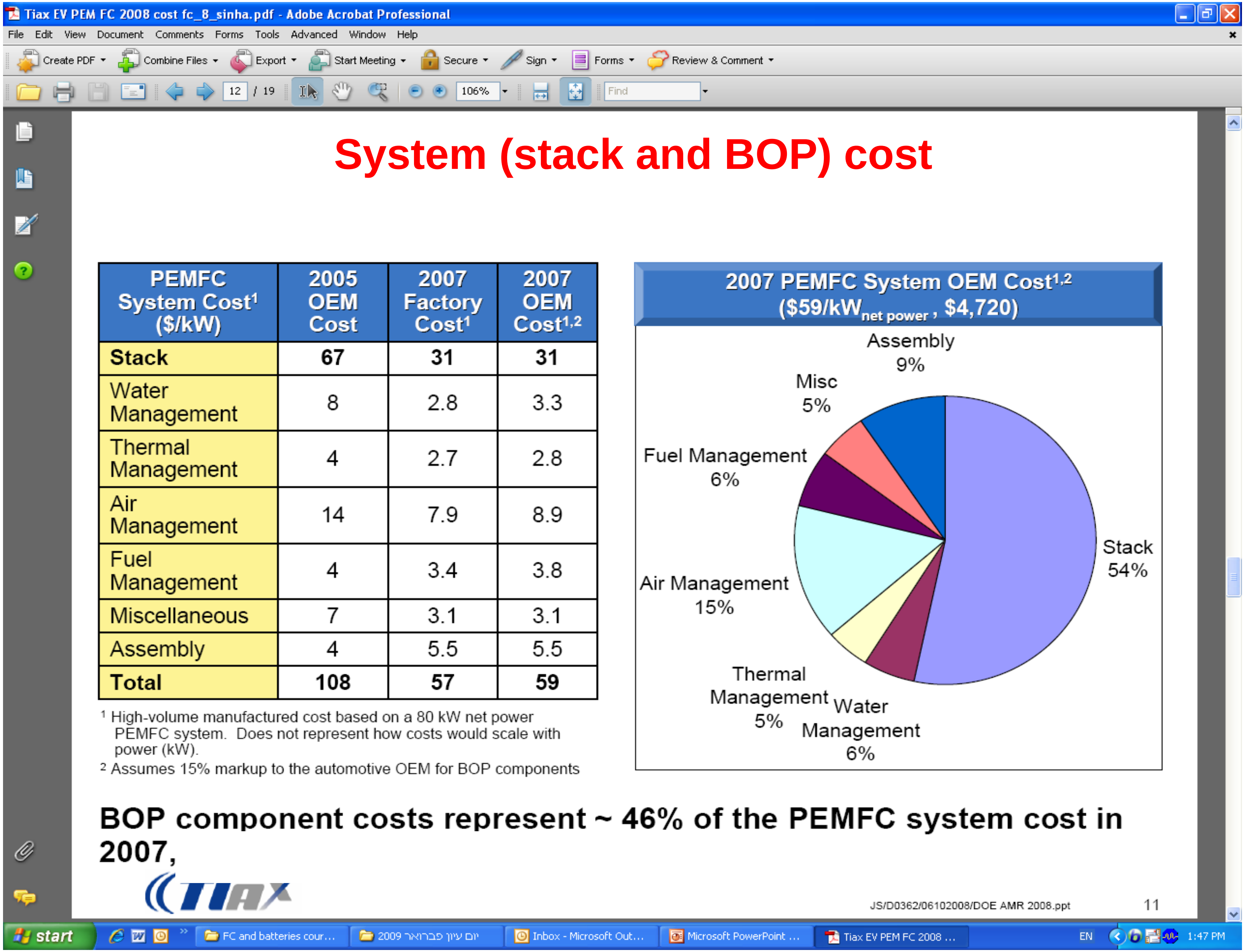
Yr 2001 MEA Cost Breakdown (MEA Cost: $152/kW)



180 grams Pt (0.8 mg/cm^2) for 0.8V @ 250 mW/cm^2

*Basis: 50 kWe net, 500,000 units/yr. Not complete without assumptions.

While power density determines the actual amount of material in the system. Parasitic power losses further increase size and cost.



System (stack and BOP) cost

PEMFC System Cost[1] ($/kW)	2005 OEM Cost	2007 Factory Cost[1]	2007 OEM Cost[1,2]
Stack	**67**	**31**	**31**
Water Management	8	2.8	3.3
Thermal Management	4	2.7	2.8
Air Management	14	7.9	8.9
Fuel Management	4	3.4	3.8
Miscellaneous	7	3.1	3.1
Assembly	4	5.5	5.5
Total	**108**	**57**	**59**

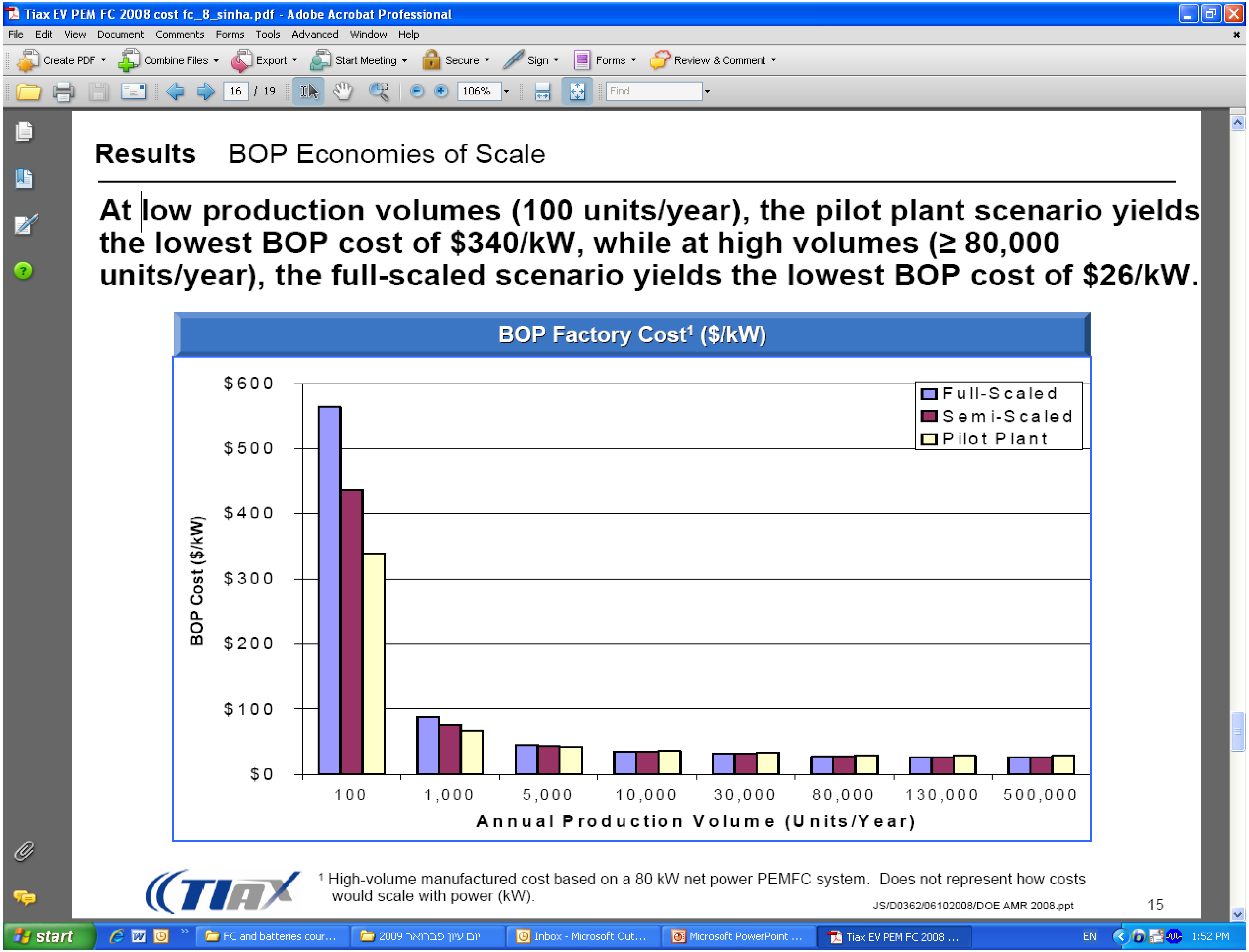
[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

[2] Assumes 15% markup to the automotive OEM for BOP components

2007 PEMFC System OEM Cost[1,2] ($59/kW$_{\text{net power}}$, $4,720)

BOP component costs represent ~ 46% of the PEMFC system cost in 2007,

TIAX



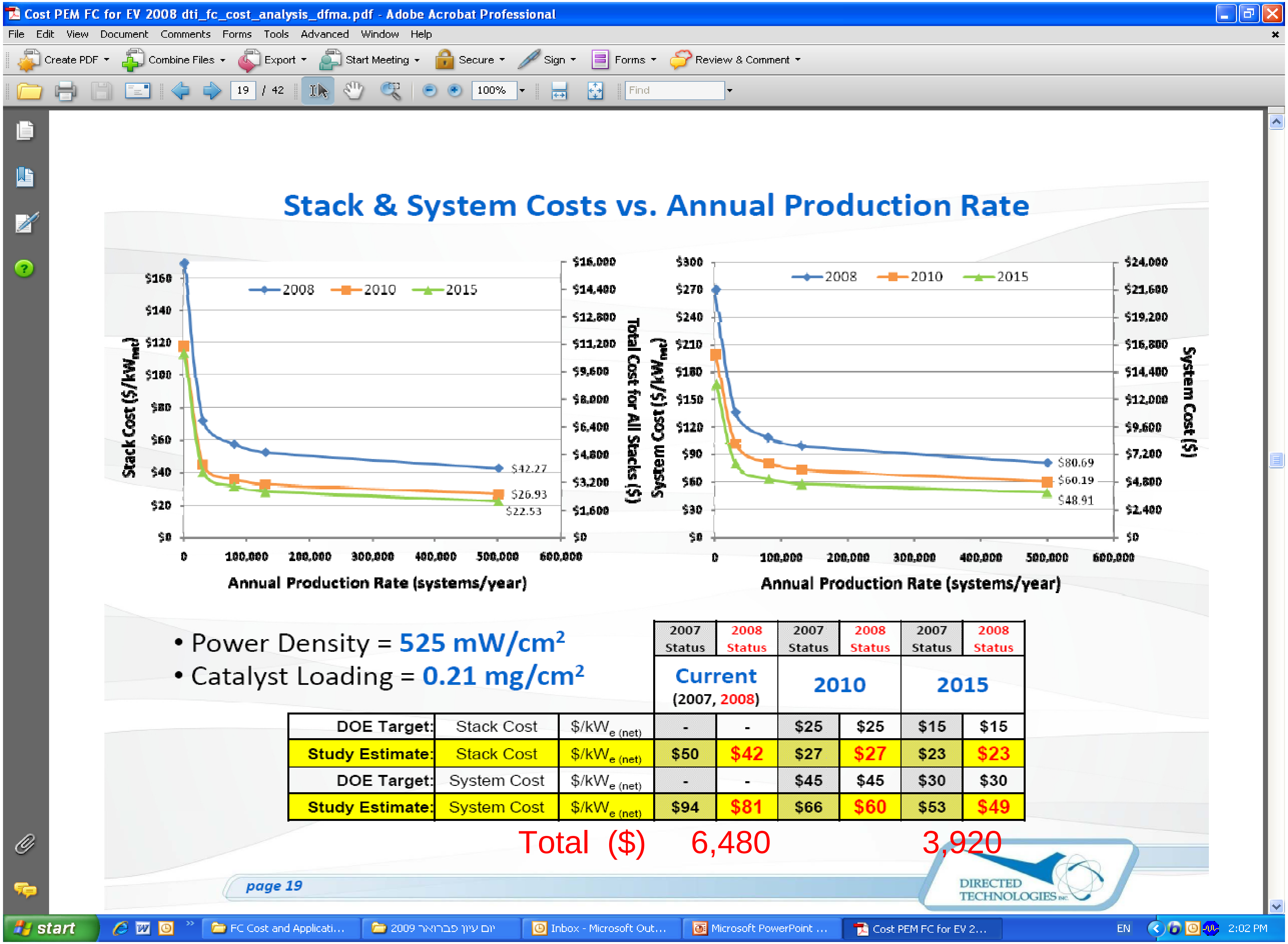
Results BOP Economies of Scale

At low production volumes (100 units/year), the pilot plant scenario yields the lowest BOP cost of $340/kW, while at high volumes (≥ 80,000 units/year), the full-scaled scenario yields the lowest BOP cost of $26/kW.

BOP Factory Cost[1] ($/kW)

TIAX

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).



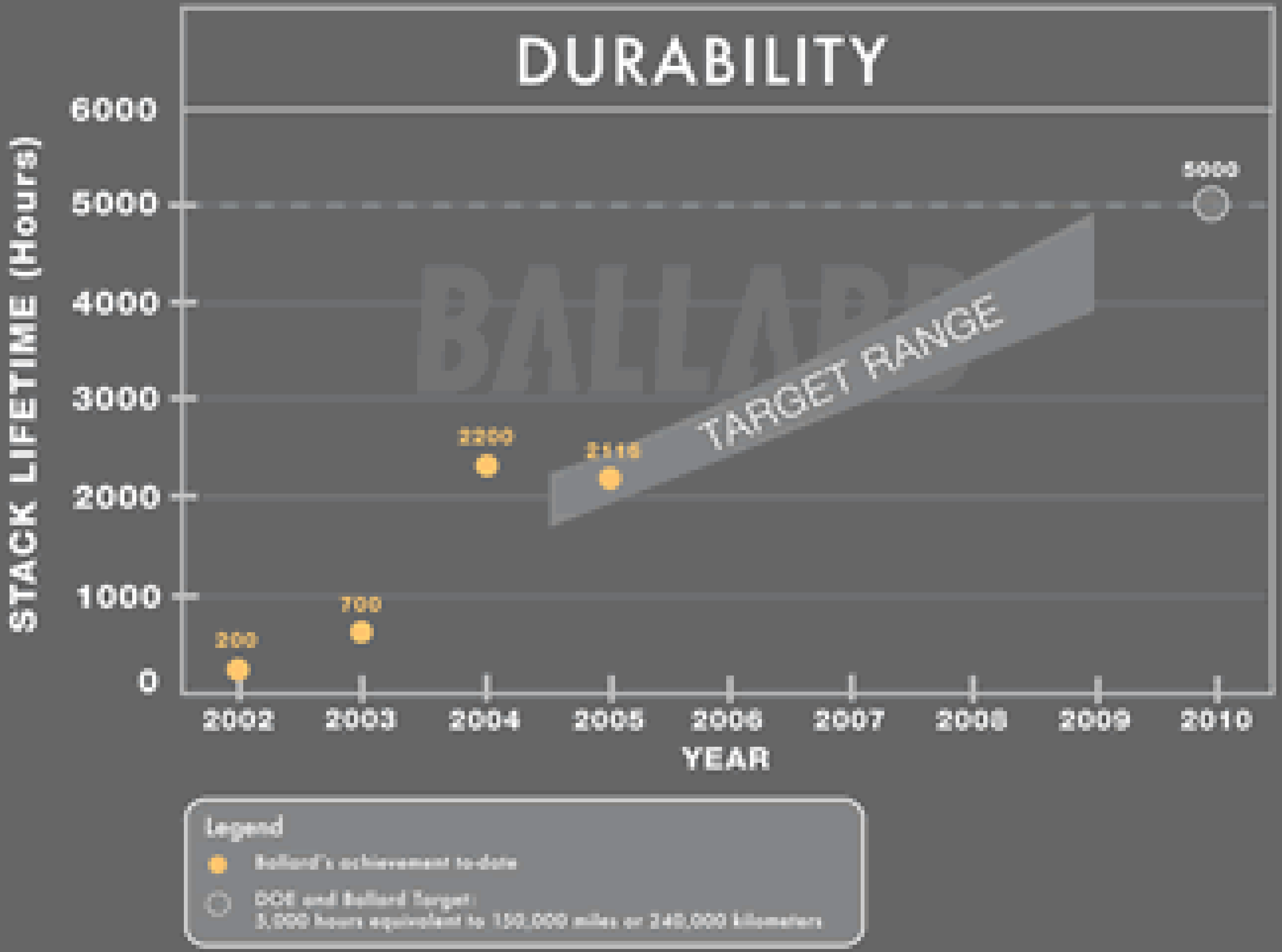
Stack & System Costs vs. Annual Production Rate

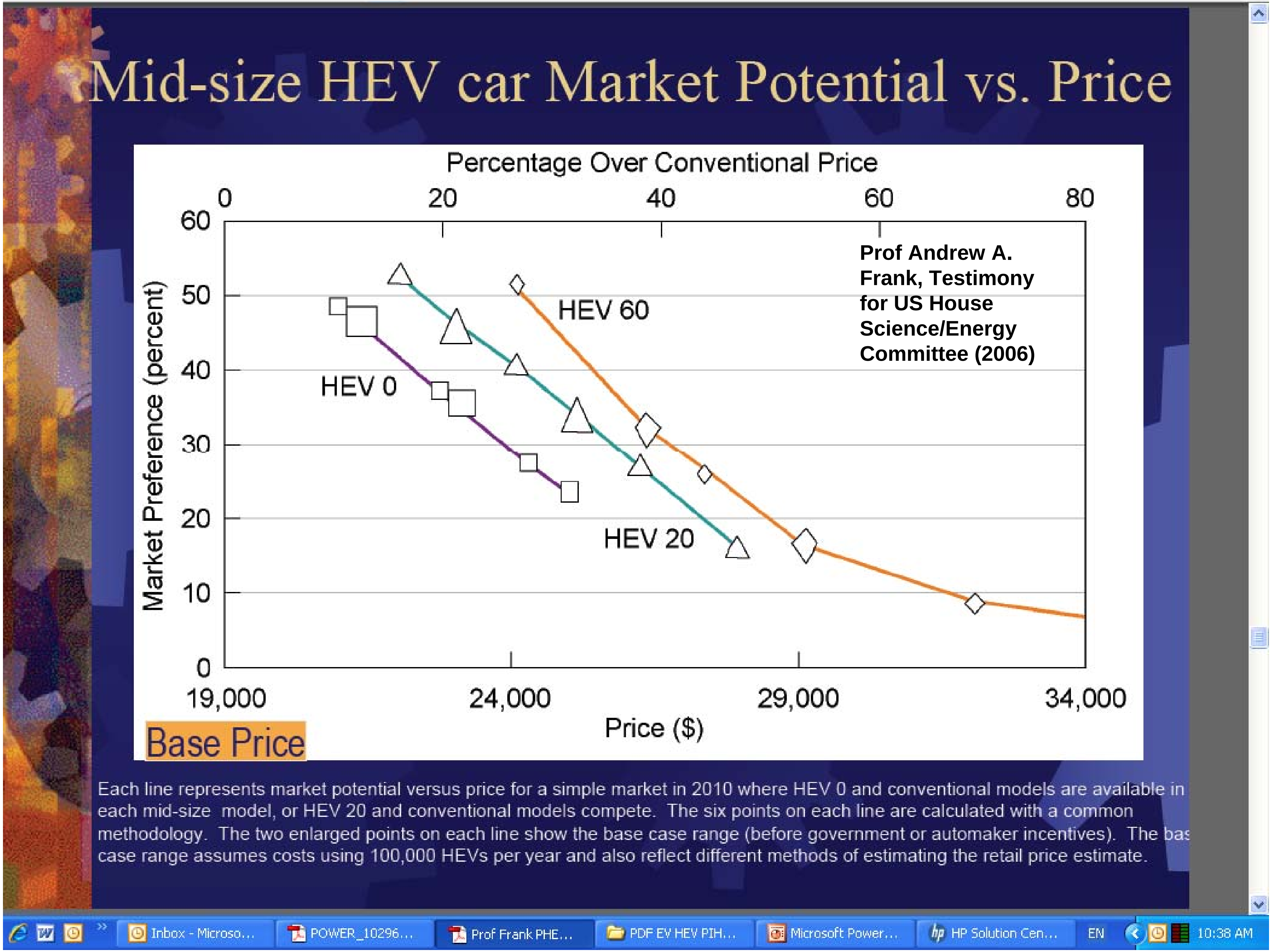
- Power Density = **525 mW/cm^2**
- Catalyst Loading = **0.21 mg/cm^2**

			Current (2007, 2008)		2010		2015	
			2007 Status	2008 Status	2007 Status	2008 Status	2007 Status	2008 Status
DOE Target:	Stack Cost	\$/kW$_{e\ (net)}$	-	-	\$25	\$25	\$15	\$15
Study Estimate:	Stack Cost	\$/kW$_{e\ (net)}$	**\$50**	**\$42**	**\$27**	**\$27**	**\$23**	**\$23**
DOE Target:	System Cost	\$/kW$_{e\ (net)}$	-	-	**\$45**	**\$45**	**\$30**	**\$30**
Study Estimate:	System Cost	\$/kW$_{e\ (net)}$	**\$94**	**\$81**	**\$66**	**\$60**	**\$53**	**\$49**

Total ($) 6,480 3,920

DURABILITY


STACK LIFETIME (Hours)
6000
5000
4000
3000
2000
1000
0
YEAR
2002
2003
2004
2005
2006
2007
2008
2009
2010
200
700
2200
2115
5000
TARGET RANGE
BALLARD
Legend
Ballard's achievement to-date
DOE and Ballard Target:
5,000 hours equivalent to 150,000 miles or 240,000 kilometers



Mid-size HEV car Market Potential vs. Price

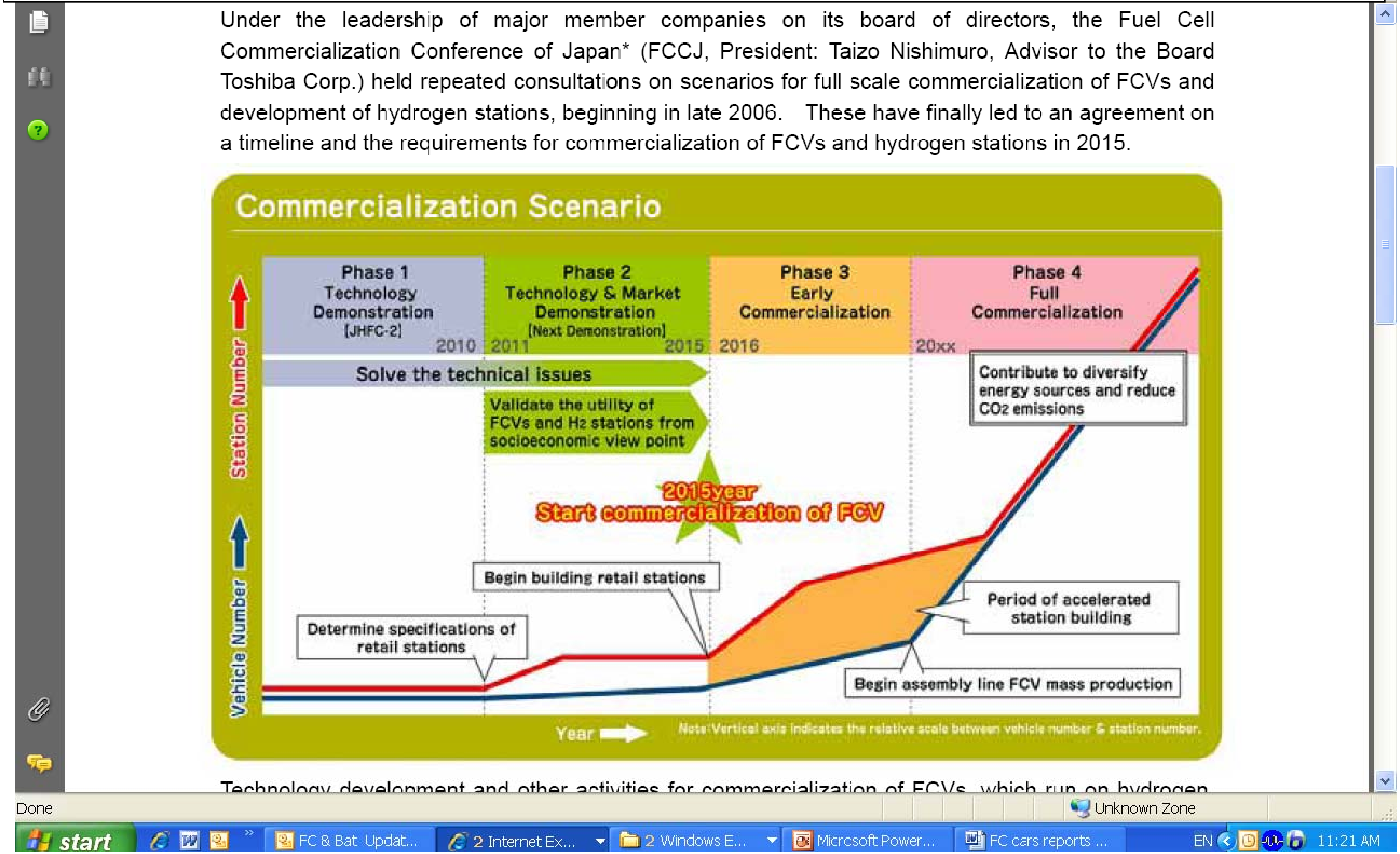
Prof Andrew A. Frank, Testimony for US House Science/Energy Committee (2006)

Base Price

Each line represents market potential versus price for a simple market in 2010 where HEV 0 and conventional models are available in each mid-size model, or HEV 20 and conventional models compete. The six points on each line are calculated with a common methodology. The two enlarged points on each line show the base case range (before government or automaker incentives). The bas case range assumes costs using 100,000 HEVs per year and also reflect different methods of estimating the retail price estimate.

Commercialization of fuel cell vehicles and hydrogen stations to commence in 2015 (FCCJ)

July 4, 2008



Under the leadership of major member companies on its board of directors, the Fuel Cell Commercialization Conference of Japan* (FCCJ, President: Taizo Nishimuro, Advisor to the Board Toshiba Corp.) held repeated consultations on scenarios for full scale commercialization of FCVs and development of hydrogen stations, beginning in late 2006. These have finally led to an agreement on a timeline and the requirements for commercialization of FCVs and hydrogen stations in 2015.

Technology development and other activities for commercialization of FCVs, which run on hydrogen

Summary

- Most large auto manufacturers are developing FCHV (billion dollars per year).
- Hydrogen cost will be at least twice that of gasoline. Thus FCHV efficiency must be twice higher (as expected).
- FC system cost must be reduced to about $50/kW (20% higher than that of ICE; major cost items are the membrane and the catalysts)
- Durability must exceed 5000 hours (twice that of today).
- The FC system size and weight (including fuel tanks) must equal (or be closed to) that of gasoline car (seems possible).
- FCHV safety (including the battery) must be demonstrated.
- Early commercialization is expected to start at 2016, full commercialization at 202x.

Thank you all for your attention!

פעילות המרכז

1. מתן יעוץ ושרותי אפיון של רכיבי תאי דלק ותאי דלק לתעשיה ולמוסדות המחקר.
2. מתן עזרה בפיתוח ייעודי של רכיבי תאי דלק ותאי דלק.
3. מתן עזרה בפיתוח ייעודי של סוללות, קבלי על, תאים סולריים וחומרים מתקדמים כגון : חומרים ננומטריים, פולימרים מוליכי חשמל, וממסים ומלחים חדשניים.
4. מדידות אנליטיות, אלקטרוכימיות מבניות ומשטחיות.
5. יעוץ מקצועי לתעשיה ולחברות start-up.
6. לרכז את השת״פ עם קבוצות תעשיה ואקדמיה לצורך קידום מו״פ.
7. עזרה בפתרון בעיות קורוזיה ברחבי הארץ.
8. הכשרת תלמידי מחקר ומשתלמים בתר דוקטורים.
9. עריכת ימי עיון.

Cost and performance Issues

- ICE cost is \$40/kW, FCs must meet this cost.
- In order to meet it membrane cost must be \$30/m^2 or less (today \$600) and platinum catalyst loading must be about 0.1 mg/cm^2 (or \$5/kW), today it is 0.5 mg/cm^2.
- Hydrogen cost will be at least twice that of gasoline. Thus FC efficiency must be twice higher.
- ICEs delivers about 1kW/l, the FC system must meet this value (it is about 0.7kW/l).