PHEVs: the Technical Side
(Plug-in Hybrid Electric Vehicles)

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California Cars Initiative (www.CalCars.org)

Slides and notes posted at
http://www.calcars.org/downloads
Introduction and outline

- Why PHEVs
  - A confluence of threats
  - Alternate energy sources are limited
    - Biofuels, other fossil fuels, H2
  - Electricity
    - Efficient, existing infrastructure, renewable potential, inexpensive, low emissions incl. CO2
    - BEVs are limited
  - PHEVs
    - Can provide 50-90% of BEV fuel displacement
    - Use existing technology
    - Can quickly become economically viable
Introduction and outline (con’t)

• PHEVs
  – Pure EV range vs. blended
  – Batteries – capabilities and risk
  – Auto manufacturers
  – Imaginary scenarios
  – What needs to happen
  – CalCars’ efforts, successes, and challenge

• Slides and notes posted at http://www.calcars.org/downloads
NOTES: Introduction and outline

• Much of data is US-centric, even CA
  – PHEVs effective in Europe++ too
  – A rapidly-deployable partial solution to many immediate global challenges.

• Paper in EET-2007 proceedings
  – Far more detailed
  – Does not exactly follow these slides

• Slides and notes posted at http://www.calcars.org/downloads
Why PHEVs?

• A confluence of threats, all requiring rapid changes
  – Global warming
  – Petroleum shortages
  – Politics

• Ground transportation plays a major part in these threats, due to
  – CO2 emissions
  – Petroleum consumption
NOTES: Why PHEVs?

• A confluence of threats, all requiring rapid changes
  – Global warming
    • Without major decreases in worldwide greenhouse emissions within a decade, this may drastically change the face of the earth
    • 80% worldwide emissions reductions cited as needed by 2050
    • Emissions are instead growing by 3%/year vs. 1%/year in 1990
  – Petroleum shortages
    • Already global demand is within a few percent of global supply capacity
    • Consumption in China and India is increasing rapidly
    • Extraction has been far exceeding new discoveries for years
  – Politics
    • Oil-using countries are becoming increasingly dependent on imports
    • Most comes from unstable middle-eastern dictatorships and theocracies

• Ground transportation plays a major part in these threats
  – CO2 emissions:
    • 30% worldwide
    • 40% in the USA
    • Up to 50% in California [check reference]
  – U.S. petroleum
    • Ground transportation accounts for 2/3 of consumption
    • 2/3 is imported at great and increasing cost
Why PHEVs?

- Alternate energy sources are limited
  - Gasoline and Diesel are very dense but engine efficiencies are low
    - Tank-to-wheels efficiencies in average driving
      - Gasoline: 14% @ 9.2 l/100km => 1900 effective Wh/kg
      - Diesel: 18% @ 7.2 l/100km => 2400 effective Wh/kg
      - Strong HEV: 24% @ 5.4 l/100km => 3200 effective Wh/kg
    - 85% source-to-tank efficiency
  - Biofuels
    - Biodiesel can run in existing Diesel engines
    - Ethanol can run in flex-fuel gasoline engines
    - Current sources compete with forests and/or food production
    - Even with advanced sources, can get only 1/3 of U.S. transportation requirements from U.S. raw materials
NOTES: Why PHEVs?

• Alternate transportation energy sources are limited
  – Gasoline and Diesel are very dense storage media
    • Current fuel-to-input-energy ratio is around 6.6:1 (85% source-to-tank efficiency)
    • Both have around 13400 Wh/kg
    • At the wheels, 13400 Wh could propel a car 107 km (67 mi) @ 8 km/kWh
    • Average tank-to-wheels efficiencies of automotive engines in use
      – Gasoline: 14% @ 9.2 l/100km (26 mpg) => 1900 effective Wh/kg
      – Diesel: 18% @ 7.2 l/100km (33 mpg) => 2400 effective Wh/kg
      – Strong HEV: 24% @ 5.4 l/100km (44 mpg) => 3200 effective Wh/kg
  – Biofuels
    • Biodiesel can run in existing Diesel engines
      – Mostly from oil-bearing crops
      – Depolymerization can allow use of organic wastes
    • Ethanol can run in flex-fuel gasoline engines
      – Around US$150 extra during manufacture
      – From corn, the fuel-to-input-energy ratio is only around 1.4:1 (30% source-to-tank efficiency)
      – From cellulose is becoming viable
  • Current sources compete with forests and/or food production
    – World corn prices have already risen from U.S. ethanol manufacture
  • CA & US lab studies show, even with advanced sources, only enough potential raw material to satisfy 1/3 of U.S. transportation requirements
Why PHEVs?

- **Alternate energy sources are limited (con’t)**
  - Other fossil fuels
    - Tar sands and coal
    - Natural gas
  - Hydrogen (H2)
    - *Very* hard to store, either as a gas, a liquid, or a compound
    - Currently usually made from natural gas
    - Can be from renewable sources, which generate electricity
      - Conversion via electrolysis, 50-67% efficient
  - Vehicle use is via
    - Fuel cell, approx. 40% efficient (20-27% electricity-to-wheels)
    - ICE, approx. 14% efficient (7-9% electricity-to-wheels)
- $1,000,000,000,000 in new U.S. infrastructure required
NOTES: Why PHEVs?

- Alternate transportation energy sources are limited (con’t)
  - Other fossil fuels
    - Tar sands and coal
      - Very inefficient extraction and/or conversion processes
      - Total CO2 emissions several times that of gasoline or Diesel
    - Natural gas
      - Can be compressed or liquified – each has limitations
      - Can be burned in slightly modified ICEs (internal combustion engines)
      - CO2 and criteria emissions are less than for petroleum
  - Hydrogen (H2)
    - Very hard to store, either as a gas, a liquid, or a compound
      - Leakage could itself become a major greenhouse gas contributor
    - Currently usually made from natural gas
      - H2 fuel cell vehicles have lower mileage from natural gas than ICE vehicles running on natural gas
    - Can be from renewable sources, which generate electricity
      - Conversion via electrolysis, 50-67% efficient
    - Vehicle use is via
      - Fuel cell
        » Approx. 40% efficient (20-27% electricity-to-wheels)
        » Very expensive and short-lived despite billions spent in R&D over decades
      - ICE
        » Approx. 14% efficient (7-9% electricity-to-wheels)
  - $1,000,000,000,000 in new U.S. infrastructure required
Why PHEVs?

• **Electricity**
  – Has existing infrastructure with unused capacity
  – Is an efficient transport medium
  – Has renewable potential
    • Most renewable energy sources produce electricity
  – Is inexpensive
    • 1/4 to 1/8 the price of gasoline!
    • US$2700-7000 saved over 100,000 km
NOTES: Why PHEVs?

• **Electricity**
  - **Has existing infrastructure with unused capacity**
    - All developed countries have electricity distributed everywhere
    - Nighttime use is typically less than half capacity
  - **Is an efficient transport medium**
    - Most renewable energy sources already generate electricity
    - Generation in fossil fuel plants is 35-60% efficient, and it may become economic to sequester the CO2 emissions
    - A battery electric vehicle can present 70-80% of input electric energy at the vehicle’s wheels
    - In contrast, the 20-27% H2 fuel cycle from the same electricity has 1/3 to 1/4 the efficiency
  - **Has renewable potential**
    - Most renewable energy sources produce electricity
    - Most charging is done at times of the day when windpower peaks
      - Vehicle charging can increase the windpower the grid can accept
      - Austin, TX, is promoting PHEVs so they can put up more wind turbines
  - **Is inexpensive** – US$2700-7000 saved over 100,000 km of driving
    - CA: gasoline is ~$3.50/gallon
      - $0.044/km for a Prius; $0.088/km for an average US passenger car
    - CA nighttime electricity is ~$0.085/kWh
      - $0.011/km at 8 km/kWh
        » 1/4 gasoline for an HEV
        » 1/8 gasoline for an ICE
Why PHEVs?

• **Electricity is clean**
  – CO2 (source-to-wheels emissions per km)
    • In U.S, already as low or lower than gasoline or Diesel
    • In California, much cleaner
    • Lower than EU’s upcoming 130 g/km tank-to-wheel requirements
    • Renewable content increasing each year
    • Individuals can opt to consume only renewable energy
  – **Criteria emissions**
    • None from vehicles
    • Generation emissions capped in US
  – **EVs are the only vehicles that get cleaner rather than dirtier as they age**
NOTES: Why PHEVs?

• Electricity is clean
  – CO2 (source-to-wheels emissions per km)
    • In U.S, already as low or lower than gasoline or Diesel
    • In California, much cleaner
    • Lower than EU’s upcoming 130 g/km tank-to-wheel requirements
    • Renewable content increasing each year
      – By law in many states incl. CA
      – EPRI projections: 40% CO2 reduction by 2050 w/o mandate
  • Individuals can opt to consume only renewable energy
  – Criteria emissions
    • None from vehicles
    • Generation emissions capped in US
  – EVs are the only vehicles that get cleaner rather than dirtier as they age
### Why PHEVs?

- **Source-to-wheels CO2 emissions for a Prius-sized passenger car**
  - 216 gm/km, gasoline @ 9.2 l/100km (26 mpg)
  - 194 gm/km, Diesel @ 7.2 l/100km (33 mpg)
  - 127 gm/km, HEV @ 5.4 l/100km (44 mpg)
  - 167 Watt-hr/km, EV @ 16.7 kWh/100km (see table below)
  - PHEV-20 (32 km EV range): 30% EV (much more when sold to those whose driving patterns best fit PHEV use)
  - PHEV-60 (96 km EV range): 70% EV

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All emissions are below the EU’s upcoming 130 g/km *tank*-to-wheels requirements.
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All emissions are below the EU’s upcoming 130 g/km tank-to-wheels requirements
Why PHEVs?

- Battery electric vehicles (BEVs or EVs)
  - Currently limited to specialized applications despite recent battery advances
  - Range is limited by weight and size
  - Batteries are expensive
  - Charging requirements are limiting
NOTES: Why PHEVs?

• Battery electric vehicles (BEVs or EVs)
  – Currently limited to specialized applications despite recent battery advances
  – Range is limited by weight and size
    • Usually to 160 km or less
      – Tesla has 320 km, but at US$100k for a small car
    • ~100 Wh/kg vs. 1900-3200 (plus tank & ICE) for petroleum
    • ~??? Wh/l vs. 1400-2400 for petroleum
    • US$300-1000/kWh
  – Batteries are expensive
    • US$500/kWh => $80/km of passenger car range
    • Cycle and calendar life may be shorter than vehicle life
  – Charging requirements are limiting
    • Unusual high-power electric circuits (e.g. 240V @ 50A)
    • Multi-hour charge rates limit long-distance driving
      – Acceptance rate of most batteries is limited
      – Fast charging requires massive circuits and electronics
      – Petroleum is effectively dispensed at >1000 kW
        » Range added at 133 km/minute
        » Equivalent to 480V @ 2100A
      – In contrast, 240V @ 50A is 12 kW
        » 1.2% as fast
        » Range added at 1.6 km/min
PHEVs: the Technical Side

PHEVs

- Are hybrids with a small extra fuel tank (the battery)
  - Used first
  - Refilled – usually overnight – from the electric grid
    - cheaper, cleaner, local fuel
- Can provide 30-70%+ of EV fuel displacement without the limitations
  - The average daily distance driven in the U.S. is 48 km
    - EPRI study: an electric range of 64 km can provide 50% of average daily driving from electricity
    - Liquid fuel requirements can be reduced by 50-80% from non-hybrids
      - Low enough to eventually be supplied completely by biofuels!
  - Overnight charging can be done from an ordinary household outlet
    - Fast charging is unnecessary
    - Overnight charging uses off-peak electricity
NOTES: PHEVs

• Are hybrids with a small extra fuel tank (the battery)
  – Used first
  – Refilled – usually overnight – from the electric grid
    • cheaper, cleaner, local fuel
  – In the U.S, 30-100 km electric range is most effective

• Can provide 30-70%+ of EV fuel displacement without the limitations
  – The average daily distance driven in the U.S. is 48 km
    • EPRI study: an electric range of 64 km can provide 50% of average daily driving from electricity
      – PHEVs sold to customers with driving patterns best suited to PHEVs will see far higher average driving from electricity
    • Average daily distance is probably lower in the Europe, making PHEVs even more effective per EV range
  – When the battery is depleted, the vehicle merely becomes an efficient hybrid, burning liquid fuel
    • Liquid fuel requirements can be reduced by 50-80% from non-hybrids
      – Low enough to eventually be supplied completely by biofuels!
  – Overnight charging can be done from an ordinary household outlet
    • Fast charging is unnecessary
    • Overnight charging uses off-peak electricity
PHEVs: the Technical Side

PHEVs

• Use existing technology
  – CalCars’ demonstration of Prius PHEVs
  – Batteries are available now
  – Mass produced conversion kits

• Are economically viable
  – Lowest lifetime cost once PHEV batteries are mass produced (EPRI study)
  – V2G (Vehicle to grid): “Cash-back hybrids”
    • Can return grid energy from PHEVs
    • Can provide line regulation and even peaking services
    • Power companies are eager to pay US$2000 or more per year
    • This can make PHEVs economically as well as environmentally compelling
NOTES: PHEVs

- **Use existing technology**
  - CalCars first demonstrated turning mass-produced (Prius) hybrids into PHEVs
    - Significant oil displacement despite low tech batteries and lack of optimization
  - **Batteries are available now that can do the job (more below)**
    - Several companies are gearing up to mass produce conversions
- **Are economically viable once PHEV batteries are produced in automotive quantities**
  - **Lowest lifetime cost once PHEV batteries are mass produced (EPRI study)**
    - Li-ion laptop cells already sell for <US$250/kWh
    - At US$500/kWh, a 50 km, 8 kWh battery pack would cost US$4000
      - US$2500 over the estimated US$1500 for a full hybrid’s pack
      - Extra battery cost equals 100,000 km fuel savings vs. a hybrid
  - **V2G (Vehicle to grid): “Cash-back hybrids”**
    - Can return grid energy from PHEVs
      - Requires smart electric metering, not yet available
    - **Can provide line regulation and even peaking services**
      - Services that otherwise require expensive, inefficient, polluting spinning reserves and peaking plants
      - If this depletes the PHEV battery
        - It merely becomes an ordinary hybrid
        - An EV would strand its driver
  - **Power companies are eager to pay US$2000 or more per year**
    - A V2G PHEV’s regulation and peaking services are that valuable
    - **This can make PHEVs economically as well as environmentally compelling**
    - V2G increases the PHEV battery’s cycle life requirements
      - Batteries are available with sufficient cycle life
      - US$2000/year could more than buy a battery replacement if needed
PHEVs: the Technical Side

PHEVs

• Batteries – capabilities and risk
  – NiMH batteries, already used in hybrids, can power PHEVs with up to 30 km electric range
  – Li-ion batteries are ideal
    • High specific energy (80-120 Wh/kg) and energy density
    • Solutions exist for thermal runaway (fire) problems
    • Extensive battery management electronics is required
    • Batteries that can do the job are now available
      – Sufficient lifetime claims, but too new to have a track record in vehicles
      – Even accelerated life testing takes a long time
      – Not yet in the volume of production to provide compelling pricing
  – Recycling is already standard
  – Less expensive future possibilities
NOTES: PHEVs

• Batteries – capabilities and risk
  – NiMH batteries, already used in hybrids, can power PHEVs with up to 30 km electric range
    • Proven reliable and long-lived in both EVs and hybrids
    • At 45 Wh/kg, would add e.g. 80 kg to a Prius
      – Would be lower power and cost per kWh than existing
      – At US$600/kWh, $1500-2000 over current battery
  – Li-ion batteries are ideal
    • High specific energy (80-120 Wh/kg) and energy density
    • Solutions exist for thermal runaway (fire) problems
      – Phosphate or other non-runaway chemistry
      » A123, Altairnano, Electrovaya, and Valence
      » Potentially low cost, but high now due to low volume
      – Pack design with small cells and propagation avoidance
    • Extensive battery management electronics is required
      – Also potentially inexpensive in high volume production
    • Batteries that can do the job are now available
      – Sufficient lifetime claims, but too new to have a track record in vehicles
      – Even accelerated life testing takes a long time
      – Not yet in the volume of production to provide compelling pricing
  – Recycling is already standard
  – Less expensive future possibilities
    • Firefly lead-acid with graphite foam plates
    • Nickel-zinc
    • Zebra Sodium-sulfur (currently too low power)
    • EStor high-specific-energy ultracapacitors (very speculative)
PHEVs: the Technical Side

PHEVs

• Vs. auto manufacturers
  – In 2004, all manufacturers said
    • PHEVs are impractical
    • No one will want to plug in a vehicle
  – Today
    • All have PHEV development programs
    • Both Toyota and GM say they want to be the first to introduce a mass-produced PHEV
    • Daimler-Chrysler has a few prototype PHEV Sprinter vans in the field
    • Toyota’s 2008 Prius is to have Li-ion batteries but not plug in
    • GM has two PHEVs in preparation
    • Ford has shown a concept prototype fuel cell PHEV SUV
    • All say that the batteries aren’t ready, and refuse to commit to a timeline
      – None are willing to use already-proven NiMH
      – All have many-year, US$100M+ technology and manufacturing requirements for battery qualification
NOTES: PHEVs

• Vs. auto manufacturers
  – In 2004, all manufacturers said
    • PHEVs are impractical
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  – Today
    • All have PHEV development programs
    • Both Toyota and GM say they want to be the first to introduce a mass-produced PHEV
    • Daimler-Chrysler has a few prototype PHEV Sprinter vans in the field
      – Will not commit to a production program
    • Toyota’s 2008 Prius is to have Li-ion batteries but not plug in
      – Toyota wants experience with Li-ion hybrids before building a PHEV
      – Toyota is quoting Dr. Anderman of the Advanced Automotive Battery Consortium, saying that PHEV impact is at least a decade away
    • GM has two PHEVs in preparation
      – A PHEV version of its 2008 improved Saturn Vue hybrid
      – The innovative Chevy Volt, being production engineered
      – Two battery suppliers have been contracted to design PHEV packs
        » A collaboration of A123 and Cobasys (an existing automotive supplier)
        » A collaboration of Saft and Johnson Controls (an existing automotive supplier)
    • Ford has shown a concept prototype fuel cell PHEV SUV
    • All say that the batteries aren’t ready, and refuse to commit to a timeline
      – None are willing to use already-proven NiMH
      – All have many-year, US$100M+ technology and manufacturing requirements for battery qualification
PHEVs

- Imaginary scenarios
  - If all U.S. passenger cars and light trucks
    - Were suddenly strong hybrids
      - Oil consumption and CO2 could be reduced by up to 40%
    - Were suddenly PHEVs
      - Oil consumption could be reduced by an additional 50-70%, eliminating all petroleum imports
      - CO2 would also be further reduced by 50-70% times the proportion of the additional electricity requirements produced from renewable sources
      - Additional windpower, already competitive with fossil fuels, would be encouraged by a ready, intermittent-friendly demand
  - The fleet would be largely PHEVs within 10 years after most production becomes PHEVs
NOTES: PHEVs

• Imaginary scenarios
  – If all U.S. passenger cars and light trucks
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PHEVs: the Technical Side

PHEVs

• What needs to happen
  – History: the Prius
    • First sold in Japan in 1997
    • The third generation (2004+) was the first to sell in large quantities
    • After 10 years
      – 1+ million hybrids (all brands) have been sold worldwide
      – Around 1% penetration
  – We need demonstration/test fleets in customer hands immediately
    • If it takes 5 years to qualify batteries and bring out the first PHEV, it could take 15 years to reach 1% penetration – far too slow to mitigate threats
    • Advantages of immediate demonstration fleets
      • Good-enough batteries are available now
      • First can be after-market conversion kits
      • Next can be conversions by Qualified Vehicle Modifiers (QVMs) working with manufacturers
  – Manufacturers can follow with PHEVs within 3-5 years from now
    • Already-developed emissions, economy, and battery testing standards and regulations
    • Already-developed customer awareness and demand
    • Designs refined by data gathered from the demonstration and QVM fleets
    • Introductions into multiple vehicle lines at once
NOVES: PHEVs

- **What needs to happen**
  - **History: the Prius**
    - First sold in Japan in 1997
    - The third generation (2004+) was the first to sell in large quantities
    - After 10 years
      - 1+ million hybrids (all brands) have been sold worldwide
      - Around 1% penetration
  - **We need demonstration/test fleets in customer hands immediately**
    - If it takes 5 years to qualify batteries and bring out the first PHEV, it could take 15 years to reach 1% penetration
      - This is far too slow to mitigate global warming or fuel shortages
  - **Advantages of immediate demonstration fleets**
    - Increase public awareness and demand
    - Provide real-world battery and control scheme testing
    - Provide a ramp-up of demand for small manufacturers of new-technology batteries
    - A head start in developing emissions, economy, and battery testing standards
  - **Good-enough batteries are available now**
    - Insufficient pre-testing risks can be handled, by
      - Early consumer (e.g. fleet owner) awareness and willingness
      - Government incentives, credits, and demonstration-fleet-friendly regulations
      - A third-party warranty provided, e.g. by a consortium of battery manufacturers, power companies (who could then use batteries too worn out for vehicles), government, and other interested parties
  - **First can be after-market conversion kits**
    - Hundreds to thousands
    - Not optimized, due to lack of knowledge of or ability to change OEM hybrid system
    - OEM warranty issues
    - Potential emissions and crash-worthiness issues
  - **Next can be conversions by Qualified Vehicle Modifiers (QVMs) working with manufacturers**
    - Thousands to tens of thousands
    - Optimized by engineering collaboration with the OEMs
    - Warranty, emissions, and crash-worthiness issues all handled
  - **Manufacturers can follow with PHEVs within 3-5 years from now**
    - Already-developed emissions, economy, and battery testing standards and regulations
    - Already-developed customer awareness and demand
    - Designs refined by data gathered from the demonstration and QVM fleets
    - Introductions into multiple vehicle lines at once
PHEVs

- CalCars’ efforts, successes, and challenge
  - In 2004, CalCars did the first PHEV conversion of a mass-produced hybrid (a 2004 Prius)
    - Several companies have since sprung up to do PHEV conversions
    - CalCars has created a do-it-yourself Prius conversion
      - Done twice in public, and filmed for a segment of PBS’s Quest
      - Being documented at www.eaa-phev.org
  - Due partially to CalCars’ efforts
    - Public awareness of PHEVs has soared, with extensive U.S. and worldwide media coverage
    - PHEVs are now being promoted by a whole range of organizations and governments
    - Several national laboratories – Argonne, NREL, etc. – have PHEV research programs
    - All auto manufacturers now have PHEV programs
NOTES: PHEVs

- CalCars’ efforts, successes, and challenge
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    - Public awareness of PHEVs has soared, with extensive U.S. and worldwide media coverage
    - PHEVs are now being promoted by a whole range of organizations and governments
      - Plug-in Partners, including many cities and counties
      - Set America Free
      - Plug-in America
      - Some national evangelical groups
      - The California Air Resources Board, the Southern California Air Quality Management District, etc.
      - Even President Bush (CalCars’ converted Prius appeared on the Whitehouse website)
    - Several national laboratories – Argonne, NREL, etc. – have PHEV research programs
    - All auto manufacturers now have PHEV programs
PHEVs: the Technical Side

PHEVs

• CalCars’ efforts, successes, and challenge (con’t)
  – PHEVs will not help solve our environmental, energy supply, and political threats until a significant and growing proportion of vehicles are PHEVs
    • Despite all collective efforts
      – There are less than four dozen PHEVs in the world today
      – Not even conversions are being mass-produced
      – No auto manufacturer has committed to a PHEV introduction date
      – CalCars is still operating on a shoestring budget with a paid staff of two
  – We have our work cut out for us!
NOTES: PHEVs

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