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

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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
  - CO_2 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**

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    - **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
  - **PHEV-60 (96 km EV range): 70% EV** driving patterns best fit PHEV use)

Location	EV g/kWh	EV g/km	PHEV-20 (32 km)	PHEV-60 (96 km)	EV, % of gasoline	EV, % of Diesel	EV, % of HEV
California 2004	236	39	101	65	18%	20%	31%
U.S. 2004	615	103	120	110	48%	53%	81%
U.S. 2010	500	84	114	97	36%	43%	66%
U.S. 2050	375	63	108	82	29%	32%	50%

All emissions are below the EU's upcoming 130 g/km *tank*-to-wheels requirements

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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

- 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

- **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

- 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

- **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

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    - **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**
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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

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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**
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  - **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**
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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**

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    - **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

- **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!**

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    - **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!**