ECE 398GG – ELECTRICAL VEHICLES

1. Introduction and Overview

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US GHG NET EMISSIONS AND INTERNATIONAL COMMITMENTS


Copenhagen Accord and Paris Agreement targets
# BIDEN ADMINISTRATION’S CLIMATE GOALS

<table>
<thead>
<tr>
<th>sector</th>
<th>goal for the year</th>
</tr>
</thead>
<tbody>
<tr>
<td>US economy</td>
<td>2030: GHG emission reduction by 50%</td>
</tr>
<tr>
<td>transportation</td>
<td>2030: set up of 500,000 EV chargers</td>
</tr>
<tr>
<td>buildings</td>
<td>2030: C footprint reduction by 50%</td>
</tr>
<tr>
<td>power &amp; energy</td>
<td>2030: 80% zero C</td>
</tr>
</tbody>
</table>
THE ORIGINAL BIDEN PLAN: 2.6 TRILLION $
THE ELIMINATED AND THE SHRUNK PARTS OF THE BIDEN PLAN

THE PARTS THAT REMAINED UNCHANGED OR INCREASED

THE SENATE BIPARTISAN PLAN: 550 BILLION $
CRITICAL IMPORTANCE OF ELECTRICITY

- Energy is the *lifeblood* of modern society
- The importance of electricity is on the rise
- Efficient and environmentally sensitive electricity services are key requirements for the nation’s global competitiveness
- The *US* power industry valued above $2.3 trillion is among the world's largest industrial sectors; 2020 retail sales revenues dipped below 400 billion $
Electricity will continue to substitute for less efficient and less productive energy forms.
US ENERGY – RELATED $CO_2$ EMISSIONS BY SECTORS: 1990 – 2020

source: U.S. energy information administration https://www.eia.gov/outlooks/aeo/pdf/08%20aeo2021%20emissions.pdf; p. 2
US CO$_2$ INTENSITY BY END–USE SECTOR: 1990 – 2020

source: U.S. EIA, available on-line at https://www.eia.gov/outlooks/aeo/pdf/08%202021%20emissions.pdf; p. 4
GLOBAL ENERGY–RELATED $CO_2$ EMISSIONS: 1990 – 2020

GLOBAL $CO_2$ EMISSIONS FROM FOSSIL FUELS

THE WORLD ECONOMIES RELY ON ABUNDANT AND AFFORDABLE ELECTRICITY
2020 US GENERATION BY SOURCE

total generation = 4,009 TWh

- natural gas 40.3%
- coal 19.3%
- nuclear 19.7%
- hydro 7.3%
- petroleum/other gases 0.4%
- other renewable sources 12.5%

2020 NET GENERATION OF RENEWABLE ENERGY SOURCES

total renewable generation = 792 TWh

- Wind: 44.0%
- Hydroelectric: 37.6%
- Solar: 11.8%
- Wood/biomass: 4.8%
- Geothermal: 2.2%

CONCERNS FROM 2021 *US GHG* ESTIMATES

- The *US* economy and the *GHG* emissions remained below pre – pandemic levels
- *Rhodium Group* estimates, based on preliminary 2021 data, that economy-wide *GHG* emissions increased 6.2 % relative to 2020, even though emissions remained 5 % below the 2019 levels
- The increase in coal-fired electricity generation accompanied by the rapid rebound in road transportation – primarily freight – are largely the
CONCERNS FROM 2021 US GHG ESTIMATES

drivers of the increase in the 2021 GHG emissions

- Goldman Sachs’s estimate of GDP growth in 2021 is 5.7% and, therefore, the growth of emissions outpaced that of the economy.

- Bottom line: the reversal in progress in GHG reductions from 22.2% below 2005 level in 2020 to 17.4% in 2021 moves the US further away from its 2025 and 2030 targets.
US GHG EMISSIONS BY SECTOR: 2005 - 2021

THE $CO_2e$ UNITS

- The GHG emissions which include $CO_2$ and other GHG, e.g., methane ($CH_4$), nitrous oxide and ozone, are expressed in $CO_2e$ or $CO_2$ equivalent.

- The unit $CO_2e$ represents the amount of a GHG whose atmospheric impact is standardized to that of 1 unit mass of $CO_2$, based on the GHG’s global warming potential (GWP).

- By definition, $CO_2$ has a GWP of 1; methane has a GWP of about 25 using a 100–year time horizon.

- The meaning is that every ton of $CH_4$ emission is equivalent of 25 tons of $CO_2$ emissions.
US GHG EMISSIONS AND ANNUAL CHANGES: 2019 – 2021


million metric tons CO$_2$e

- **transportation**: 1,700,000 (2019), 1,550,000 (2020), 1,750,000 (2021), change: +10%
- **industry**: 1,600,000 (2019), 1,530,000 (2020), 1,590,000 (2021), change: +3.6%
- **electricity**: 1,600,000 (2019), 1,690,000 (2020), 1,440,000 (2021), change: -10%
- **buildings**: 1,000,000 (2019), 1,020,000 (2020), 920,000 (2021), change: -7.6%

2020: -7.6% + 1.9%
2021: +10%
US TRANSPORTATION FUEL CONSUMPTION: 2020 – 2021


change with respect to 2019 in %

2020

2021
US ELECTRICITY GENERATION
BY SOURCE: 2005 - 2021


share of total GWh electricity in %

coal
natural gas
nuclear
renewables

US ELECTRICITY GENERATION BY SOURCE: 2019 - 2021


- Natural gas: 37% (2019), 40% (2020), 37% (2021)
- Coal: 24% (2019), 20% (2020), 23% (2021)
- Nuclear: 20% (2019), 21% (2020), 20% (2021)
- Renewables: 17% (2019), 19% (2020), 20% (2021)
US GHG NET EMISSIONS AND INTERNATIONAL COMMITMENTS


- net emissions
- Copenhagen Accord and Paris Agreement targets
EV DEPLOYMENT GOAL: CLEAN THE AIR

source: ACEA, CAAM, EA-Volumes; available online at https://www.weforum.org/agenda/2021/02/electric-vehicles-europe-percentage-sales/
KEY EV BENEFITS

- Replacement of fossil fuel by electricity is a very effective way to reduce fossil fuel consumption – an important objective for decarbonization, given the heavy reliance of transportation on such fuels.

- Various studies have shown that it is possible to integrate EVs into grids in a way that economies-of-scale effects can reduce the electricity prices via the efficient management of supply to meet EV loads.
KEY $EV$ BENEFITS

- $EV$s are viewed as deferrable loads on the electric grid – such flexibility is extremely useful since $EV$ batteries can both absorb and inject electricity, in line with the needs of the grid.
- Wider $EV$ deployment can be a driver of deeper penetrations of renewable resources and increase the harnessing of such resources.
- The replacement of fossil fuels by electricity for transportation provides an effective pathway for $GHG$ emission reductions in the economy.
THE SINGLE BIGGEST EV HURDLE

- The key barrier to the realization of the EV benefits is the low sales of EVs to date.

- The two key causes for the low sales stem from:
  - range anxiety
  - sheer lack of EV charging facilities

- Some factual information is of interest:
  - in 2015, EV sales were less than 1% of the US auto sales – of the 17.4 million passenger vehicles sold, 116,597 or 0.7% were EVs.
THE SINGLE BIGGEST EV HURDLE

- since the start of EV sales in 2010, total US EVs sold by 2015 numbered 407,136 – 0.16% of the total US passenger fleet

- global EV sales grew 60% from 2014 to 2015

By 2015, it was clear that the cost per mile of an EV was well below that of an ICEV mile in various jurisdictions around the world.
### COMPARISON OF US $/MILE COSTS OF EVs AND ICEVs: 2015

<table>
<thead>
<tr>
<th>Country</th>
<th>ICEV $/mile</th>
<th>EV $/mile</th>
<th>EV savings $/mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>DK</td>
<td>0.16</td>
<td>0.20</td>
<td>-0.04</td>
</tr>
<tr>
<td>US</td>
<td>0.16</td>
<td>0.16</td>
<td>0.00</td>
</tr>
<tr>
<td>ES</td>
<td>0.16</td>
<td>0.14</td>
<td>0.02</td>
</tr>
<tr>
<td>DE</td>
<td>0.16</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>CN</td>
<td>0.16</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>EU-27</td>
<td>0.16</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>Global</td>
<td>0.16</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>FR</td>
<td>0.16</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>UK</td>
<td>0.16</td>
<td>0.12</td>
<td>0.04</td>
</tr>
</tbody>
</table>
**EVs ON THE ROAD**

Source: Financial Times

https://www.ft.com/content/31d68af8-6e0a-11e6-9ac1-1055824ca907

Number in use ('000)

- 1,200
- 1,000
- 800
- 600
- 400
- 200
- 0

 países:

- other
- Germany
- UK
- France
- Norway
- Netherlands
- Japan
- China
- US
CUMULATIVE *US EV SALES*: 2011–2018

Source: http://energyfuse.org/u-s-reaches-1-million-electric-vehicle-sales/
CUMULATIVE *US EV AND PHEV SALES:* 
DECEMBER 2010 – AUGUST 2020

Source: data from Argonne National Laboratory as reported by Inside EVs; available online at https://insideevs.com/news/446419/cumulative-plugin-car-sales-us-august-2020/
TESLA MODEL 3 RESERVATIONS

Source: http://electrek.co/2016/04/03/tesla-model-3-reservations-timeline/, issued April 2015
TESLA 3 MODEL ESTABLISHES US EV MARKET DOMINANCE

Source: USAFacts; available online at https://usafacts.org/articles/how-many-electric-cars-in-united-states/
## THE TOP 10 STATES FOR TESLA REGISTRATION IN 2020

<table>
<thead>
<tr>
<th>State</th>
<th>Registration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>73,800</td>
</tr>
<tr>
<td>FL</td>
<td>16,200</td>
</tr>
<tr>
<td>TX</td>
<td>10,400</td>
</tr>
<tr>
<td>NJ</td>
<td>9,700</td>
</tr>
<tr>
<td>NY</td>
<td>9,500</td>
</tr>
<tr>
<td>WA</td>
<td>7,700</td>
</tr>
<tr>
<td>IL</td>
<td>5,700</td>
</tr>
<tr>
<td>AZ</td>
<td>5,000</td>
</tr>
<tr>
<td>PA</td>
<td>4,800</td>
</tr>
<tr>
<td>MA</td>
<td>4,500</td>
</tr>
</tbody>
</table>

Source: HIS Markit
GLOBAL EV SALES

sales in millions

%  
5.4 r.o.w.  
5.9 UK  
6.2 FR  
9.9 US  
13.2 DE  
20.5 r.o.E.  
38.9 CN

US EV MONTHLY SALES: 2020 & 2021

NOTABLE TRENDS IN US EV SALES IN 2021

- EV sales reached 55,007 in October 2021, which means a 25.1% increase from August 2021; ANL EV data indicate annual sales increased by 45.9% compared to October 2020.

- Cumulative October 2021 EV sales totaled 448,434.

- Tesla models have accounted for over half (59.5%) of EV sales in October 2021.
Unlike the established automakers, e.g., GM and Ford, which closed one factory after another in 2020 – 21, Tesla had record sales each quarter with sales nearly double those in 2020.

The computer chip shortage problem seems to not have impacted Tesla to the extent the rest of the automobile manufactures were affected.
The *Tesla* car design and manufacturing relies very little on external sources – a distinct contrast to that of the current auto industry, which heavily relies on external suppliers for much of the software and computing expertise in both hardware and software; *Tesla* from its start did not outsource its coding and hardware.
Given the chip shortage situation, Tesla engineers recoded their software to replace chips in short supply by those available – an option unavailable to the other manufacturers.

In 2021, Tesla’s global sales of 936,000 EVs were nearly twice its 2020 sales of 499,550 cars; the big auto giants sold fewer cars in 2021 than in 2020.
Such solid 2021 performance is a stark turnaround from 2018, when the *Tesla* production and supply problems were rather severe.

A key cause of the manufacturing snafus stemmed from *Tesla*’s insistence on self-production of many on the *EV* components.

Other auto manufacturers have realized that they must follow *Tesla*’s approach to have control of their onboard computer systems, *e.g.*, *Mercedes* will...
customize “standardized chips” in their cars and use its own software

- The *Tesla* decision to rely on its own in–house production emulates the early days of automobile manufacturing when companies such as *Ford* owned its own steel plants and rubber plantations; the shift away from in–house production to reliance on outside production left the companies exposed to *supply-chain vulnerabilities*
A distinguishing feature of Tesla EVs is the small number of models and fewer options than those of established auto manufactures; the Tesla EVs’ fewer components use fewer chips and so Tesla’s vulnerability to supply-chain turmoil is considerably reduced.
RIVIAN TRUCK ASSEMBLY

EV REGISTRATIONS PER 100,000 RESIDENTS

Source: USAFacts; available online at https://usafacts.org/articles/how-many-electric-cars-in-united-states/
**NORWAY CAR SALES: 2012 – 2020**

**Graph:**
- **x-axis:** Years (2012 to 2020)
- **y-axis:** Percentage
- **Data Points:**
  - **diesel and petrol (including hybrids):** Decreasing trend from 90% in 2012 to 30% in 2020
  - **electric:** Increasing trend from 0% in 2012 to 40% in 2020

**Source:** Norwegian Road Federation
THE LEADING NATIONS IN E-MOBILITY IN 2020

source: ACEA, CAAM, EA-Volumes; available online at https://www.weforum.org/agenda/2021/02/electric-vehicles-europe-percentage-sales/
EV CHARGING INFRASTRUCTURE
EV CHARGING STATIONS

Source: http://4.bp.blogspot.com

Source: http://cdn2.ubergizmo.com

Source: http://www.autoconcept-reviews.com/cars_reviews/ford/ford-focus-electric-vehicle-2011
THE CONCENTRATION OF PUBLIC CHARGING STATIONS ON COASTS AND IN CITIES

Source: BloombergNEF; available online at https://www.bloomberg.com/news/articles/2021-04-30/ev-charging-industry-is-doing-everything-except-showing-a-profit
PUBLIC CHARGING STATIONS: THE MAJOR NORTH AMERICAN PLAYERS

Source: BloombergNEF; available online at https://www.bloomberg.com/news/articles/2021-04-30/ev-charging-industry-is-doing-everything-except-showing-a-profit
PUBLIC CHARGING STATIONS: THE SLOW GROWTH

source: BloombergNEF; available online at https://www.bloomberg.com/news/articles/2021-04-30/ev-charging-industry-is-doing-everything-except-showing-a-profit

thousands of charging ports

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ports</td>
<td>5</td>
<td>13</td>
<td>5</td>
<td>11</td>
<td>12</td>
<td>17</td>
</tr>
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CHICAGO DOWNTOWN PARKING LOT WITH EV CHARGING

EV CHARGING AT THE ILLINOIS STATE CAPITOL COMPLEX, SPRINGFIELD

A VEHICLE CHARGER AT THE TESLA MOTORS INC. GIGAFACTORY IN McCARRAN, NV

Source: Bloomberg photo
ROCKLIN, CA: TESLA EVs CHARGING

Source: Bloomberg photo
The Use of the Term \( EV \)

- We use the term \( EV \) to refer to plug-in vehicles, which fully or partially depend on electricity.

- We include:
  - plug-in hybrid \( EVs \) – \( PHEVs \)
  - extended range \( EVs \) – \( EREVs \)
  - battery \( EVs \) – \( BEVs \)
  - all electric \( EVs \) – \( AEVs \)

- We exclude all hybrid vehicles that cannot be plugged in.
OVERVIEW OF THE COURSE

- ECE 398GG is essentially an energy course, which examines the various facets of the electrification of transportation and its significant impacts via the replacement of internal combustion engine (ICE) vehicles (ICEVs) by EVs.

- The very nature of the topic involves multiple disciplines that range from basic physics, circuit
OVERVIEW OF THE COURSE

theory and economics to public policy, environmental analysis and regulation, and from drives and machines, *power electronics and control to sociology, market research and automotive design to vehicle safety and the set-up of the EV charging infra-structure* (*EVCI*)

❑ This course explores: the basics of how *EVs* operate; the integration of *EVs* into the grid – as
OVERVIEW OF THE COURSE

both charging and discharging distributed energy resources; the effective utilization of power electronics in EV operations and charging; the role of electric generators and drives; the environmental benefits; and machines, power electronics and control to sociology, market research and automotive design to vehicle safety and the set-up of the EV charging infrastructure (EVCI)
COURSE OBJECTIVES

- Expose students to the high, *strategic* importance to the power industry of the emerging market of electrified transportation
- Provide adequate background to understand the multi-disciplinary nature of *EV* and *EVCI* topics
- Cover in adequate depth the diverse aspects of energy systems, electro-mechanical energy conversion, motors, drives, generators, power
COURSE OBJECTIVES

electronics, electricity grids together with the relevant public and regulatory policy, economics and environmental issues

☐ Serve as an “unofficial” gateway course to students who wish to pursue the specialized senior level courses offered by the Power and Energy Systems faculty
Introduction and general overview

- salient features of transportation industry
- key drivers of transportation electrification
- history of EVs in transportation sectors
- energy and environmental issues
- global EV deployment and e-mobility
- course objectives and scope
TOPICAL OUTLINE

- Vehicle dynamics and energy/power requirements
  - basic physics of rolling vehicles
  - gravity, aerodynamic drag, hill climbing and descent, rolling resistance & braking forces
  - tractive force determination
  - the role of inertia, acceleration/deceleration
  - energy/power requirements for vehicle rolling motion; energy storage/transfer impacts; illustrative examples
Key EV design and operations considerations

- EV size and weight
- Range implications
- Vehicle parameters and performance metrics – their nature and typical values
- Definition and role of drive cycles in performance assessment
- Performance evaluation
TOPICAL OUTLINE

- *EV* Architectures and configurations
  - the major *EV* subsystems – motors, drives, inverters, batteries and energy storage, chargers, sensors and control
  - architectural structures and configurations
  - generator sets and hybrid subsystems

- Energy Conservation Principle
  - the energy invariance principle that underlies all of nature’s processes
  - illustrative examples
  - “wells to wheels” energy tracking
The EV batteries and their management
- key portable energy requirements beyond rechargeability
- key battery components: roles and nature
- electrochemical cell as the building block of battery packs; modules and packs
- battery operations phases – charging, discharging and idle
- battery features
- major figures of merit – capacity, storage capability, efficiency, health, life, energy density, specific power, state of charge (s.o.c.), depth of discharge, voltage/current characterization, temperature and geometry
- today’s dominance of Li-ion batteries and
Basic principles of, and design considerations in, EV electric motors and generators

- concepts of *electromechanical energy conversion*
  - energy, co-energy, force and torque
- review of low-frequency electromagnetics (EM) and EM force calculations of shear stress, machine power density and efficiency
- comparative assessment and equivalent circuits of motor types – induction, surface and internal permanent magnet, switched and synchronous reluctance
Electric drives for traction application in EVs
- basic nature and role of electric drives in electro-mechanical energy conversion
- fundamentals of electric drives and their operation from an EV perspective; the DC–AC conversion process and approaches to generate controllable AC waveforms
- traction inverters and their control
- inverter applications to EV acceleration, deceleration & constant speed maintenance
ECE 398GG ELECTRIC VEHICLES (EVs)

TOPICAL OUTLINE

- **EV** integration into today’s grids
  - the impacts of **EV** loads on distribution grids
  - **EVs** as a deferrable load
  - **EVs** as distributed *storage resources* and the *vehicle-to-grid* (V2G) concept
  - role of **EV** aggregations

- **EV** energy efficiency analysis and evaluation
  - the *wells-to-wheels* reference metric used for internal combustion engine vehicles (ICEVs)
  - cumulative impacts of the constituent efficiencies – electricity generation
efficiency, grid efficiencies, charging efficiency and battery-to-wheels efficiency

- definition and evaluation of efficiency metrics – miles per gallon equivalent and kWh per 100 miles

- key assumptions; data sources

- **EV** Environmental Attributes
  - quantification of **EV GHG** emissions & comparison with the **ICEV** “tailpipe” emissions
  - evaluation of **EV** lifecycle emissions
  - **EV** battery life extension and disposal
ECE 398GG ELECTRIC VEHICLES (EVs) TOPICAL OUTLINE

- **EV Battery Charging Fundamentals**
  - voltage levels and charging types
  - charging connectors
  - charging process; protection issues

- **EV battery charging power electronics**
  - AC grid analysis – power system in the sinusoidal steady state, complex power, single and three-phase power, average power and circuit analysis
ELECTRIC VEHICLES (EVs) TOPICAL OUTLINE

- power electronics topics: the analysis of DC – DC converter operations in the continuous conduction regime and PWM rectifier circuit analysis; applications in EVSE – EV supply equipment – and the implementation of EV charging stations; specification of basic and buffer requirements; power converter types for the EV charging levels; and, DC fast buffer charge

- technology implementations and challenges
The EV charging infrastructure (EVCI)
- the critical role EVCI plays to enable massive EV adoption; interdependence and interactions of EVCI with existing infrastructures
- the establishment of EVCI: principal objectives
- roles renewable and storage energy resources play; their effective integration into EVCI
- location/implementation of EVCI stations
- current EV charging providers and their business models; identified gaps and major challenges
- policy and regulatory aspects
Policy and Regulatory Issues
- the nature/scope of policies to drive stronger EV sales and EVCI station implementation
- policy formulation and implementation at various levels of government
- EV adoption policies and incentives
- replacement of the gasoline tax funding source in an electrified environment

Beyond EVs
- further transportation electrification in airplanes, buses and freight mobility
- battery technology enhancements
- wireless charging
A JOBY AVIATION EVTOL AIRCRAFT OUTSIDE THE NYSE

SERIOUS PARIS TESLA ACCIDENT ON DECEMBER 11, 2021

source: FranceNews24, twitter; https://twitter.com/FranceNews24/status/1469952264941056005
TESLA MOVES HQ FROM PALO ALTO, CA, TO AUSTIN, TX

source: Austin American-Statesman; available online at https://www.statesman.com/story/business/2021/10/07/tesla-moving-headquarters-austin-texas-elon-musk-shareholder-meeting/6008861001/