Carlo Alberto Amadei

EPS 239: Term Paper

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PREMISE

By playing with the spreadsheet, I soon realized that there were needed solutions that would contribute in an 83% reduction of CO_2 emissions by 2050, such as electrification of the transportation or an overall increase in the efficiencies. However, in order to reach the overall target, other solutions had to be implemented and this generates a multitude of possible scenarios. Nevertheless, depending on the main innovative technology characterizing a particular scenario, it is possible to identify, what I called, “extreme scenario”. An extreme scenario allows reaching the goal by mainly betting on a single technological solution, and I individuated three extreme scenarios, which are represented with a ternary plot in Figure 1.

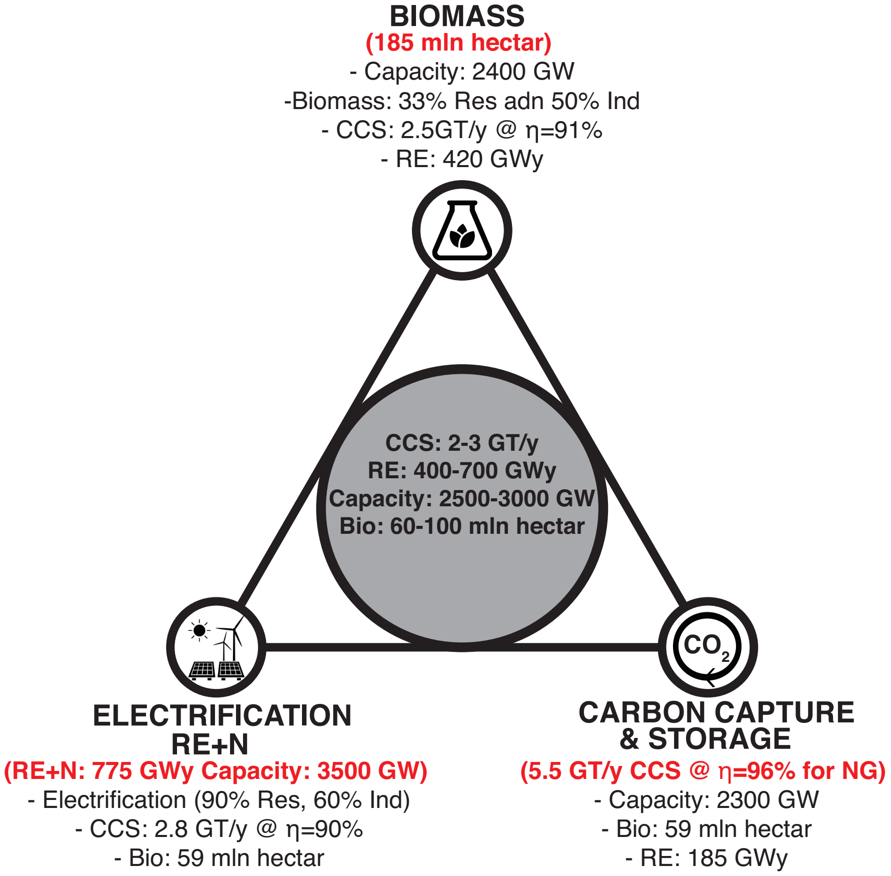

Figure 1: Three extreme scenarios and in red the main technological solution for ach scenario to reach the emissions reduction goal. In grey the main features of the scenario used in the spreadsheet.

Biomass scenario. This scenario requires 185 mln hectares of land (10 dry ton/hectar yield) designated to biomass production, which will generate 33% and 50% of the energy required for residential and commercial (R&C), and industry, respectively.

Carbon Capture and Storage (CCS). This scenario requires 5 GT/y with 96% capture efficiency of emissions from natural gas (NG) plants.

Electrification: This system requires a considerable increase in the grid capacity to almost 4000 GW with high penetration of nuclear and renewable energy (RE).

In this paper, instead of focusing on one of the mentioned scenario, I decided to take a less risky path by trying to combine more technologies instead of betting on just one technology. The main features of the selected scenario are at the intersection of the three scenarios and are highlighted with a grey circle inside the ternary plot. In this paper, the scenario is described in details with the solutions needed for each of the sectors (transportation, R&C, industrial, and energy generation). Moreover, one can read near-term policies to support this transition to a less polluting economy. The reader will also find a discussion of the main technological challenges that we discussed in class, such as expansion of the grid, biomass and food production competition, high penetration of renewable, etc.

TRANSPORTATION

The transportation in US heavily relies on petroleum with 92% share in 2015.[1] The heavy reliance on petroleum, not only is one of the major responsible of US greenhouse gas emissions (GHG) with a ≈ 30% share, but also has created potential risks for the American economy and national security. In fact, US import almost 3.5 billion barrels/y of crude oil and each day more than 50% of the world's oil supplies transits in one of six maritime chokepoints,[2] which are vulnerable to attacks that could cause the oil price to skyrocket.

The net GHG emissions from the transport sector significantly increased in the last 20 years (+25%) compared to the other sectors, and an in inversion of this trend is auspicable,[3] in order to have cleaner and more reliable means of transportation.

The scenario aims to have 85% of the passenger vehicle transportation electrified by 2050, which will require ≈20% and ≈85% of electric vehicle (EV) sales penetration by 2025 and 2040, respectively (considering a car lifetime of approximately 10 years). This is a tremendous effort considering that, as of September 2016, there were circa 500000 legal EV, which is less than 0.2% of the car market share.[4] The amount of electricity needed to power an EV is mostly driven by the vehicle weight, thus, lightweight EV could more easily replaced passenger vehicle compared to heavy-duty trucks. In order to tackle this electrification challenge, it is important that there will be a democratization of EV and the selling of Tesla model 3 for $35000 is paving the road in this direction.[5] The reduction in the cost of this EV was mainly due to a more efficient way to build batteries. This trend (EV democratization) has to be supported by the sales of hybrid electric vehicles (HEV), which can further drive down the cost of battery and or introducing disruptive storing technology. In this sense, Panasonic is developing a new and more efficient battery technology, in which silicon is combined with the graphite used in convention lithium-ion batteries. Additional push to EV could be related to an increase of the oil price. The 15% of passenger vehicle moved by fossil fuels will be divided between oil and liquid natural gas (LNG), which is a demonstrated technology in Europe, with almost 1.5 million registered vehicles.[6] The scenario also foresees a 25% reduction of vehicles-mile traveled and an overall automobile demand reduction due to improved mobility strategies, such as carpooling, improved public transportation and bicycle commuting. A recent DOE investigation showed that a 18% reduction in US GHG emissions could be achieved with changes in the build environment, such as high-density walkable communities.[7] A high-density community is characterized by diverse land use, easy accessibility, and it reduces the distance to transit.

Although there a was a lot of press regarding to the Tesla Model U pickup, it will m difficult to see heavy-duty trucks powered by batteries due to physical limitation on the weight. For this reason, more than one third of the freight will be still relying on fossil fuel in 2050. The paradigm shift is that the oil-powered trucks will mainly be replaced by less polluting LNG-powered trucks. As discussed earlier for passenger vehicles, this is could be implemented considering that in European market with more than 1% of trucks which are already powdered by compressed LNG (e.g. >200000 units). A sign of the feasibility of a switch to LNG is the installation of LNG lanes in Texas, Louisiana and California.[9] Moreover, LNG is already used as a fuel for vessels on inland waterways, such as ferries in Norway, and could be used in ships. However, the remaining freight will switch to electric vehicles. That is, electric busses, electric trains, hybrid trucks for medium-weight trucks.

Regarding the flight, electrification will probably not be a viable option, but considering that almost 50% of purpose of air travel is due to business, a reduction of circa 50% due to new experience of virtual reality can be foreseen. On the other hand, preventing people from using a flight for travelling will be more difficult…

RESIDENTIAL and COMMERCIAL SECTOR

The US buildings sector accounted for almost 40% of the primary energy consumption in 2016; more energy than any other end-use sector.[10] While new buildings can be constructed with high energy performance levels, the existing stock is predominantly of poor energy performance and consequently in need of renovation work. Considering a renovation rate of 2-3% (today at 1.5%), we could assume that by 2050 all the buildings will be renovated. With renovation, a building could increase its efficiency and/or reduce its energy demand by 25%. This seems to be a realistic metric, supported by a DOE report stating that a building energy use could be cut of 20% with current us technologies, but it could be >30% if research goals of new technologies will be met. The key technological aspects for demand reduction in buildings are dependent on the geographical location.

Cold climate. Tightly sealed structures with proper ventilation can decrease the need of heating by 20% to 30%.[11] This could be achieved by high level of insulation in walls, high-performance windows characterized by low thermal transmittance, and minimization of thermal bridges

Hot climate. In these regions, the effort should focus in having reflective surfaces (i.e. cool colored roofs).

In order to decrease the lighting, new buildings should be constructed by optimizing the window to wall ratio, orientation, possible building facade and by using more efficient light emitting diode (LED).[11] Moreover, the energy required for a house can be reduced by the controlling of lighting, cooling, and heating via building automation (i.e. smart home/appliances), which is a fast growing market predicted to double its value by reaching the $10 billion mark by 2020. A concrete example of the implementation of smart appliance can be identified with the reduction of phantom energy (electronics that are turned off but continue to draw power by being plugged into an outlet), which accounts for almost 10% of the household electric use.[12]

The implementation of energy-efficient solutions should prompt even more the R&D in highly insulated window, advanced thin insulation, low-cost reflective coating, passive ventilation, and improved heat pumps using solid-state materials in order to meet a possible 35% decrease in energy demand.

Overall, the 2050 scenario will also have a high electrification (80%) of the R&C sector compared to the 50% of today. The 30% excess will be mainly used for the implementation of heating, ventilation and air conditioning (HVAC) systems. HVAC provides the thermal comfort (cooling and heating) and the an acceptable indoor air quality (ventilation) required for human comfort by moving heat rather than converting it from a fuel. Especially in cold climate, highly efficient heat pumps (COP between 3 and 4) could be the most viable option and the increase in sale of HVAC in North America corroborates this statement. In particular, demand for HVAC equipment in the US is expected to increase 6.8% annually reaching $20.4 billion in 2019, recording gains over twice the rate of the 2009-2014 period.[13] However, the colder the temperature outside, the less effective the heat pump is; thus, for areas with rigid winter, such as the Northeastern US, biomass heating and NG (10% compared to the amount used today) will be implemented.

The transition to more efficient buildings needs to be supported by codes to encourage "green design," such as the Leadership in Energy and Environmental Design (LEED) rating system. These codes should apply for both new and existing energy buildings and they should influence the value of the assets. Moreover, the governments need to better communicate to the public and to financial entities the economic, comfort and health benefits. For instance, depending on the climate, a better preforming building shell can have a payback time a s fast as 3 years

INDUSTRIAL SECTOR

Circa 30% of the US GHG emissions are related to energy systems, which include a broad spectrum of industries: refining, chemicals production, iron and steel production, just to mention some.[14]

As discussed for the previous scenario, a reduction in the emissions could be achieved by efficiency improvements/demand reduction and by introducing cleaner energy (electricity from RE and biomass) in a fossil fuel dominated feedstock. Regarding the increase efficiency, it is possible to forecast a ≈10% increase in the efficiency. This number is smaller compared to R&C, since the industrial sector has already implemented energy efficiency practices. For instance, the energy intensity (i.e. amount of energy to produce a unit of GDP) has been falling steadily in the last decade on average of 1.5% per year. However, further increase in the industrial processes could involve:

Motors. Using more efficient motors. Especially for electric motors, the cost of operations in its lifetime is hundred or thousand time greater than its purchase price, then a higher capital cost for a more efficient motor is justified.

Steam systems. Steam is mainly used as an energy carrier, however, almost half of the energy input might be lost before doing the intended work and this can be improved by better insulation.[15]

Operational buildings. See previous section.

Water chemistry. Treating the water used since it can carry mineral salts, organics, and microorganism that can impact the efficiency of the plant.

Heat recovery. Industrial processes could be reused the waste heat. In particular, as much as 20-50% of the energy input is lost in form of the hot exhaust gas, cooling water, and heated products is lost.[16]

Combined heat and power (CHP). CHP is an attractive option for many sectors, particularly when both electricity and heat are required in a process.

The system thinking could further increase these savings, and a recent DOE report has shown that applying systems thinking to motor systems and steam systems can save between 10% and 20% versus an equipment only saving of between 2% and 5%. Overall, the 10% projected increase in efficiency used in the spreadsheet is confirmed by the National Academy of Science Engineering and Medicine stating that non-manufacturing sectors are on track to reduce their energy intensity through 2040, resulting in a total reduction of 9.2%.[17]

In order to reduce the CO_2 emissions, there will be a 50% electrification of the energy used by industrial process. Electric energy can be used in heavy industrial sectors, such as iron and steel production, with the implementation of electric arc furnaces. The remaining 50% will be divided among NG, biomass, and a small percentage of oil. The high-energy fuels (NG, biomass, and oil) will mainly be devoted to indusial sectors, which need high temperatures (i.e. chemical, cement, iron and steel production). For instance, biomass can be used in the cement and chemical production with a technology readiness level up to 9 via two main approaches.[18,19] i) Biomass fuels are used in place of fossil fuels, e.g. directly combusted in boilers to raise steam, or ii) or converted into methane via anaerobic digestion. Moreover, biomass can also be used for steam generation in cement.[20]

In the spreadsheet, I did not considered the use of synfuel due to its limited use today and their need of coal, which leads to national security considerations. Although US has large reserves of coal, only 56% of the demonstrate reserve base is available for mining due to property rights, land se conflicts, and physical and environmental restricnctions.[25]

The R&D will have to play an important role in specific sectors. For instance, the development of new catalyst to increase the production of chemicals and designing novel separation membranes, which will allow a more performing CO_2 capture at the point source.

The biomass used in the industrial and R&C sector amounts to 951 million dry tonnes. This could be achieved by exploiting forestry resources, agricultural resources (including energy crops and crop residues), and waste resources. In particular, the most recent billion-ton report[21] stated how this number can be achieved:

Energy crops. They can be divided in herbaceous and woody, characterized by 1%/y increase in yield and they could amount to 450 million dry tonnes. Alternatively, possible biomass import from tropical countries can be considered, since it can be harvested annually.

Crop residues. It *c*ould be as high as 150-200 million dry tonnes, which is a data confirmed by other studies.[22]

Waste. This is an umbrella category including agricultural, forestry and urban waste. The amount of biomass can be as high as 200 million dry tonnes. For instance, only forest-product firms alone (including paper companies) use almost 100 millions of dry tons to power their factories.[23]

Forestry. Potential forest residues and forest thinning can be quantified as high as 100 million dry tonnes, which is confirmed by other sources.[24]

ENERGY GENERATION

The strong electrification of the three sectors (transportation, R&C, and industrial) requires an enlargement of the grid capacity. The 2050 scenario will require a conservative (i.e. annual and not seasonal) 2950 GW capacity, compared to the actual 1160 GW. In order to meet this goal, the new installed capacity per year should be roughly 50 GW, which is double the value of the new planned electric capacity installed in 2016.[26] Although, a growth of 50 GW/y will certainly be a challenge, NREL confirmed that the US has the potential to increase at this rate.[27] In 2015 and 2016, wind and solar accounted for more than 60% percent of all new electricity generating capacity in the US.[14,26] The penetration of RE will continue to increase (see details below) and they will provide circa 40% of the electricity required by 2050. Circa 75% of RE electricity production will be composed by non-dispatchable solar and wind. Needless to say that centralized storage is required in order to reduce intermittency; thus, R&D advances are needed to introduce storing technologies rather than pumped-storage hydropower, which constitutes the majority of the actual storage. Regarding the solar energy production, concentering solar power plants (CSP) could rely on thermal storage with molten salt.[28] Large photovoltaic (PV) and wind farms will be required to have a centralized storage in the critical nodes of the grid. The storage could be done with flow batteries, due to their long life span and the ability to perform a high number of discharge cycles. Although R&D will be required to overcome their design, the low energy intensity can be remediated just by making larger batteries (space in centralized storage will not be the primary constrain).[29] Note that an improvement of the grid efficiency is forecasted via reconducturing and via the use of new materials (e.g. superconductors).

Overall, the energy generation by fuel is described here below.

NG with CCS (697 GWY). The amount of NG with CCS is dictated by two factors: i) reaching the 83% reduction in CO_2 emissions and ii) an achievable/credible yearly goal for CCS. The first one was a project-constrain, whereas the second one was selected to be ≈2.5 GT/y of CO_2. This number has been chosen considering that 5-6 GT/y seems to be a predicted number for the world amount of CCS by 2050. Considering that the US will still be one of the major economies, but also a leader in R&D and new technologies, I allocated 50% of CCS to the US. However, the development of CCS at this large scale comes with great challenges.

Economics. There are still uncertainties related to CCS and there is the need of demonstrations. Thus, financial support mechanisms are needed for demonstration and early deployment of CCS in order to attract private investment.

Infrastructures. The necessary pipelines have to be built.[30]

Storage. In the US there is definitely the needed amount of geological storage. The estimations are between 2000 to 20000 GT. However, future studies need to convert this theoretical estimation in a bankable and accessible storage.

Wind (215 GWy). In 2015, 11 states generated 10% of their total electricity form wind. The DOE vision is to have more than 400 GW of wind power by 2050. This goal will be achieved by implementing offshore wind, which will be characterized by 180 GW increase compared to 2030. The offshore wind will be mainly located on the Atlantic coast due to presence of shallower water, which makes the development more attractive.[31] Considering a possible increase of the wind capacity factor to >50% due to new turbine design, the 215 GWy goal can be met.[32]

Solar (160 GWy). Price of energy of PV steadily decreased in the last 10 years. For instance, the median cost of utility-scale PV installed is steadily decreased from 6 $/W in 2008 to less than 4 $/W in 2015. At the same time the solar energy generation has increased more than 30-fold, reaching planned 9 GW installation in 2016.[26] In order to meet 160 GWy production by 2050, the solar market will be divided in three sectors: i) PV factories to generate 90 GWy, ii) CSP to generate 50 GWy, and iii) utility scale PV 20 GWy. The solar PV factories and CSP plants will be mainly located in the Southwester US and, by considering an average irradiation of 6-7 kWh/m2/day, they will extend for circa 3000 km^2.[33]

Nuclear (155 GWy). In order to meet this goal, the scenario foresees the implementation of generation IV reactors starting from 2030. Generation IV reactors are still in the R&D level, but they could meet commercial operation before 2030.[34] During the '70s, the new installation capacity of nuclear plant was ≈6-7 GW/y, thus, it will possible to achieve 155 GWy by 2050. This production will also be supported by the extension of the license of 86 reactors (82 still operating) beyond 40 years. The increase in nuclear power in US agrees with the general increase expected in the world market (from 383 GWe in 2015 to 900 GWe in 2050).[35]

There are several challenges that nuclear energy has to overcome:

Public perception. In order to overcome the public perception the best tool will be education and awareness. For instance, in March 2014 a survey reported that 67 % of citizens thought that nuclear energy directly releases GHG. Familiarity can also support to overcome this challenge and favored contacts with communities living near nuclear power plant could assist this transition.

Environmental health. This is mainly related to hazardous radioactive materials. The two main ways of nuclear waste storage are in ponds associated with the individual reactor or a common pool at a multi-reactor site. After 40 years of storage the wastes are encapsulated and buried for indefinite storage. The scientific community agrees that the geological burial is the best solution, and the construction of a nuclear fuel repository in Finland (Onkalo) and Russia (Sverdlovsk) are steps in this direction.[36]

Nuclear Safety. Generation IV reactors will be unlikely cooled by water avoiding the associated with water (leaks or boiling) and contamination of coolant water, and hydrogen explosion.

Economics. This is a controversial aspect of nuclear, but it is certain that nuclear plants will need subsides especially to cover the capital costs, which are more than 70% of the levelized cost of energy.

Terrorism. US nuclear plants need to respect federal and international regulations. They are constructed to resist to extreme conditions and are impenetrable structures; thus, it is unlikely that terrorists could turn a reactor into a Chernobyl disaster.

Other (50 Gwy). The principal actor in this category is represented by tidal power. DOE, in collaboration with researcher from Georgia Tech, mapped and quantified the availability of tidal power in then US. The reports find that tidal energy could produce 1410 TWhy. This corresponds to more than 150 GWy. Thus, by exploiting less than a third of the available sites, US could produce 50 GWy from tidal power.[37]

Hydroelectric (40 GWy). This represents around 10 GWy increase compared to the actual hydroelectric generation in the US.[38] DOE estimates that non-powered dams have potential to add 12 GW of additional generating capacity, with about 3 GW of capacity in the Ohio River region.[39] Considering the hydroelectric capacity factor (≈35%) this could add more than 4 GWy of electricity generation, whereas the remaining 6 GWy should be harvested by the construction of new dams.

Geothermal (40 GWy). Geothermal is an active market and, at the global scale, is expected to grow from the actual 13 GW to 18.4 GW by 2021. Moreover, if countries follow through on their geothermal power development goals, the global market could reach 32 GW by the early 2030s. The US is the leader country in geothermal energy with one third of the actual installed capacity.[40] If R&D studies and demonstration will validate the possibility of enhanced geothermal systems, electricity generation could be as high as 50 GWy by 2050. In the case of traditional geothermal energy, it will be difficult to achieve more than 25 GWy by 2050.[41]

Natural Gas (13 GWy). This is 10% of the actual electricity generation and it will represent a small percentage of the total NG plants in 2050.

POLICIES FOR THE NEXT DECADE

Transportation: the policies should mainly focus on the electrification of passenger vehicle. It will be needed to maintain tax benefits for EV, but at the same time local governments and energy provider should build the infrastructure for plug-in vehicles. The government should also boost the R&D in lightweight and low-cost batteries.

R&C: Federal tax credits for electrification of heating and cooling (i.e. HVAC) and biomass should continue. Introduce mandatory energy certification for buildings. Boost the R&D in smart appliances and technology aimed to reduce the energy waste in building (i.e. low transmittance materials).

Industry: Tax benefits for industries that switch energy source from oil to biomass and electricity. Display and spread the use of best available technology. Introducing a mandatory carbon footprint, similar to an energy certification of buildings. By assessing how much pollution an industry generates, it will be possible to assess the introduction of other policies. Boost in R&D for membranes to efficiently separate and capture GHG at the point source.

Energy Generation: Policies to support RE are paramount. For instance, EIA AEO2009 Reference case projection forecasted that wind capacity would grow to 44 GW in 2030. Then, EIA revised the forecast, after the introduction in February 2009 of the American Recovery and Reinvestment Act (extended and expanded incentives for both wind and solar) to 66 GW by the end 2014. The updated projection for wind capacity in 2014 was 65.9 GW, nearly identical to the actual outcome nearly six years later. R&D should focus on the development of centralized storage (i.e. flow batteries) and advanced grid management, Moreover, high incentives should be granted for demonstration of generation IV reactors and CCS.

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