

# Potential Natural Gas Impact on Cost Efficient Capacity Planning for Automakers and Electricity Generators in a Carbon Constrained World

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## ABSTRACT

Greenhouse gas (GHG) emission targets are becoming more stringent for both automakers and electricity generators. With the introduction of plug-in hybrid and electric vehicles, transportation and electricity generation sectors become connected. This provides an opportunity for both sectors to work together to achieve the cost efficient reduction of CO<sub>2</sub> emission. In addition, the abundant natural gas (NG) in USA is drawing increased attention from both policy makers and various industries due to its low cost and low carbon content. NG has the potential to ease the pressure from CO<sub>2</sub> emission constraints for both the light duty vehicle (LDV) and the electricity generation sectors while simultaneously reducing their fuel costs. To quantify the benefit of this collaboration, an analytical model is developed to evaluate the total societal cost and CO<sub>2</sub> emission for both sectors. A large-scale linear programming (LP) problem is formulated to conduct tradeoff studies between the two sectors in various scenarios, and some high level insights of cost efficient capacity planning strategies for automakers and electricity generators are then identified by solving the optimization problems. The results will show the cost differences between the two sectors working together and independently to meet the CO<sub>2</sub> emission constraints. Moreover, the results will reveal the differences in capacity planning in the scenarios when NG is available or unavailable as an alternative automobile fuel source. This will help to understand the potential natural gas impact on cost efficient capacity planning for both automakers and electricity generators in a carbon constrained world.

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## 1. INTRODUCTION

As detailed in the recent report from the International Panel on Climate Change (IPCC), atmospheric accumulation of manmade greenhouse gas (GHG), mainly CO<sub>2</sub>, is likely to have significant effect on the earth's climate. The IPCC report indicates that GHG concentrations in the atmosphere will rise to dangerously high levels unless emissions are reduced drastically [1]. The reader is referred to [2] for detailed calculations of GHG reduction targets for preventing prominent global warming. The study conducted by [3] shows that fast actions need to be taken to achieve a stable state of atmospheric CO<sub>2</sub> concentration level by 2100. In addition, natural gas (NG) is drawing increased attention from policy makers and various industries lately due to its low cost and low carbon content. NG has the potential to ease the pressure from CO<sub>2</sub> emission constraints for

both the LDV and the electricity generation sectors while simultaneously reducing their fuel costs. See [4], [5] and [6] for analysis of GHG levels of NG compared to other fuel types.

This work will focus on the interaction between the LDV sector and electricity generation sector in reducing GHG, and will study the impact of NG prices on the emission reduction strategies for both sectors. As major contributors to U.S. GHG emissions (see [Section 2](#) for more details), it is essential that both the LDV sector and electricity generation sector take actions to reduce their emissions in order to mitigate climate change. Within the existing regulations, the LDV sector and electricity generation sector are generally regulated separately. However, with the introduction of vehicles that receive power from the electric grid, such as plug in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) (see [7] and [8] for the preliminary assessment of GHG emissions from PHEVs), the two sectors are no

longer independent. The linkage between the two sectors is twofold. First, although PHEVs in electric mode and EVs have zero tank-to-wheels (TTW) emissions (i.e. tailpipe emissions), their well-to-tank (WTT) emissions are dependent on the energy source of electricity generation. Thus, an EV charged with electricity generated by coal-fired power plants can actually have more GHG emissions than a similar vehicle with a gasoline-fueled hybrid-electric powertrain [9]. Second, the increasing deployment of PHEVs and EVs adds to the electricity demand [10] and thereby forces either an increase in investment in new, low-GHG generation capacities or prolongs the operating life of existing high-GHG capacity. See [11], [12] and [13] for the impact of PHEV charging on the electricity grid, and see [14] for creating intelligent recharging grids for EVs.

There are a number of papers in the literature on reducing GHG for automakers and electricity generators individually. Morrow et al. [24] conducted a thorough comparison of the impacts of various policies that employ an economy-wide cap and trade program to reduce GHG emissions from the transportation sector. Thomas and Candy [25] simulated and compared the benefits of deploying various alternative vehicle technologies including hybrid electric vehicles (HEVs) and PHEVs fueled by gasoline, diesel fuel, natural gas, and ethanol, and EVs powered by either batteries or fuel cells, in terms of reduced GHG, and oil consumption. Reichmuth et al. [21] examined bounding cases for the adoption of individual vehicle technologies and then explored the feasibilities for different combinations of advanced vehicle and fuel technologies under given GHG reduction targets for the transportation sector. Shiau et al. [13] focused on the deployment of PHEV in the transportation sector and identified optimal vehicle designs and allocation of vehicles to drivers for minimum net life cycle cost, GHG emissions, and petroleum consumption under a range of scenarios. Shiau and Michalek [18] investigated the effects of GHG reduction regulations on the vehicle design decisions of profit-seeking firms in competition. For electricity generators, researchers have also looked into different factors which help with GHG reduction, including upgrading technologies [47], and change of fuels [48]. Venkatesh et al. [49] studied the implications of NG prices on the GHG emissions from electricity generation in the USA.

Even though there are many publications on GHG mitigation for LDV and electricity generation sector individually, there are few research studies on joint GHG mitigation for the two sectors as a whole. Supekar et al. [9] built a linear programming model for cost-efficient joint GHG reduction for both automakers and electricity generators, in which the electricity generation sector is treated exogenously and all the generator deployment strategies and emission levels are taken as given. Moreover, the facts that deployment of electricity powered vehicles adds extra demand to electricity generators and that GHG emission level of electricity powered vehicles depends on the mix of electricity generator technologies are neglected in that paper. These facts are precisely what link the two sectors together. In this paper, both the automakers and the electricity generators are treated as endogenous and can make their own decisions. In addition, we explicitly model the intertwining relationship between the LDV and electricity generation sectors because (1) the deployment of electric vehicles brings extra demand for the electricity generators, and (2) the choice of generator technologies impacts the environmental friendliness of electric vehicles.

In this paper, we study the cost efficiency of reducing GHG within the USA, between the LDV sector and electricity generation sector up to year 2050 and we address the following questions: Are the two sectors investing in the most cost efficient way from society's perspective? If not, is it more cost effective for the two sectors to work together to achieve the same total CO<sub>2</sub> emission reduction target? This research provides a framework for answering these questions using a mathematical modeling approach. We develop a LP model to determine (1) what is the most cost efficient new capacity investment strategy through a long planning horizon for each sector respectively, (2) how much capacity investment cost, operating cost and retirement cost can be saved under cooperation between the two sectors, and (3) what is the impact of NG prices on the investment strategies of both sectors.

To quantify the benefit of this collaboration between the two sectors, a model is built to include both the LDV sector and the electricity generation sector. This model plays the role of a central player that decides the investment strategies for both sectors, with the goal of minimizing the discounted total societal cost (i.e., the sum of costs from both sectors). Our goal is to provide a high level view of the best way to achieve minimum societal cost without market penetration or technology implementation limitations. Detailed analysis of consumer purchasing behaviors or market share equilibrium are beyond the scope of this paper, and interested readers are referred to [16], [17] and [18] for analyses in those fields.

Using the LP framework, a total of eight scenarios are constructed based on (1) whether the two sectors work independently or jointly to satisfy emission constraints; (2) whether natural gas vehicles (NGVs) are available for deployment in the LDV sector; and (3) whether the price of NG is \$4/mmbtu, which is equal to \$2/gasoline gallon equivalent (GGE), or \$8/mmbtu, which is equal to \$4/GGE. The model generates optimal strategies and shows their similarities as well as differences, providing insights into the impacts of emission constraints, cooperation and NG price on both sectors, and future trends of technology deployment.

This paper is organized in six sections. [Section 2](#) provides a brief overview of the climate impact of GHG emissions. [Section 3](#) describes the LP model and presents the mathematical formulation. [Section 4](#) explains the eight scenarios studied in this paper, and introduces the main input data and assumptions. [Section 5](#) presents the results and shows comparison results among various scenarios. [Section 6](#) concludes the paper with a discussion for future work.

## 2. CLIMATE CHANGE AND REGULATION

The breakdown of GHG (CO<sub>2</sub>eq.) emissions in [Figure 1](#) shows that within the U.S., electricity generation produces  $2.26 \times 10^9$  MT CO<sub>2</sub>eq annually, which is approximately 42% of total GHG emissions, and transportation contributes  $1.72 \times 10^9$  MT CO<sub>2</sub>eq annually amounting to 32% of US emissions [19]. Within the total transportation emissions, LDVs are responsible for 61% [20]. While cooperation between these two sectors and other sectors is possible, we consider only the cooperation between the electricity generation sector and the LDV sector because they are the two largest CO<sub>2</sub>eq contributors and because of the evolving interdependencies between them.

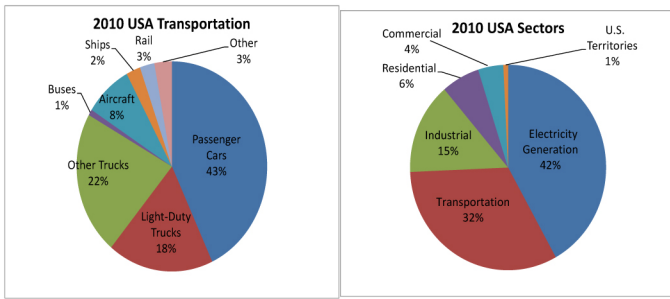


Figure 1. Breakdown of GHG (CO<sub>2</sub> eq.) emissions in 2010 (EPA 2014).

There are numerous regulations and policies in place to encourage GHG or CO<sub>2</sub> emission reduction activities for both LDV and electricity generation sectors. However, GHG emissions in LDV and electricity generation sectors are in general judged by different measures and regulated in separate systems. To regulate the LDV sector, nationwide, TTW emissions are mainly governed through the Corporate Average Fuel Economy (CAFE) regulation set by the National Highway Traffic Safety Administration (NHTSA) and through the grams of CO<sub>2</sub> per mile targets set by the United States Environmental Protection Agency (EPA). Both basically set increasing vehicle fuel efficiency targets for automakers to reduce fuel consumption and CO<sub>2</sub> emissions [21]. Analysis by the EPA shows that the CAFE regulations will result in average new vehicle fuel efficiency increasing to 35.5 mpg by 2016 [22] and to 54.4 mpg by 2025 [23].

Nationwide, EPA has the GHG Reporting Program for a wide range of industries to promote understanding of where GHG emissions are coming from and to improve the government's ability to make informed policy, business, and regulatory decisions [26]. A number of states in the US have taken actions to control GHG or CO<sub>2</sub> emissions, either state-wide or just for electricity generators. For example, California requires 80% below 1990 emission level by 2050 state-wide (Executive Order S-3-05 need references); Florida targets at 80% below 1990 levels by 2050 both state-wide and for electric utilities (EO 07-127); Minnesota sets a goal of 80% below 2005 levels by 2050 state-wide (Next Generation Energy Act); and New Mexico establishes a constraint of 75% below 2000 by 2050 state-wide (Executive Order 05-033).

Solutions do exist to achieve the emission reduction goals for both sectors, among which investing in renewable generators (e.g., solar and wind generators) and electrified vehicles (e.g., PHEVs and EVs) have received significant attention from both the government and the public. Both sectors are investing in greener technologies, such as EVs and nuclear and renewable generators to help in meeting their emission targets. From 2011 to June of 2012, about 10,000 MW of new renewable electricity generation was added, costing more than \$42 billion in capital investment [27]. Other than that, developing NG generators and vehicles is also receiving tremendous attentions in practice. Automakers are spending billions of dollars on developing and deploying HEVs, PHEVs and EVs [28].

There are examples of cooperation in investment in green capacity between the two sectors that has proved to be mutually beneficial. For example, in 2011, Ford collaborated with DTE Energy and the

Michigan Public Service Commission to install a 500-kilowatt solar photovoltaic panel system at Michigan Assembly Plant, where the Focus electric and C-MAX Hybrid and C-MAX plug-in hybrid are produced. Our study will investigate the potential cooperation between the sectors at a much larger scale and over a long time-frame and we will quantify the benefit of collaborations towards achieving CO<sub>2</sub> emission reduction [29].

### 3. METHODOLOGY

The model framework takes a high level view of the LDV and electricity generation sectors to gain insight into technology deployment strategies that can achieve a certain emission reduction target at the lowest cost. We look at the time horizon from 2011 to 2050 and require that by year 2050 the model must reduce its annual emission level to 20% of its 2010 emission level. This is set in a similar logic as the many state policies cited in Section 2. We make the annual emission target decrease by the same percentage each year from 2011 to 2050, and then we continue running the model until 2100 to avoid the "end of horizon" effect while holding 2050-2100 emission targets constant. We initialize our generator and vehicle fleet in 2010 with data of existing capacities by then. We assume that all technologies improve gradually over time; i.e., later deployed units emit less and consume less fuel than similar units deployed earlier, therefore staying consistent with general regulations such as CAFE. The model assumes that technology can leave the stock over time due to natural retirement (reaches a certain age), forced retirement (this is a decision the model makes), or due to a survival rate (e.g. accidents). The stock size increases over time, thus new deployment of technology in any year must account for both increased demand and lost capacity.

For this study, the LDV sector consists of seven light duty vehicle types: conventional vehicles (CV), natural gas enabled conventional vehicles (CV\_NGV), hybrid electric vehicles (HEV), natural gas enabled hybrid electric vehicles (HEV\_NGV), PHEV, natural gas enabled hybrid electric vehicles (PHEV\_NGV) and BEV. For each year, the composition of the fleet is tracked by both vehicle type and age. For the electricity generation sector, we consider four generator types: coal (C), NG, nuclear (N), and renewable (R). Among all the different renewable technologies, we consider wind and hydro. Hydro generation is treated as a constant each year but not a control variable. The composition of the generator stock is tracked by both generator type and age. For both the vehicles and generators, we are aware that within each type, there is a variety of generator sizes, locations, etc., and we use the average level data for each type. Each year, the decision variables for each sector include how many units of each type to deploy and how many units to forcibly retire. There are costs associated with these decisions, including deployment, forced retirement, and operating costs for both sectors. We solve for the optimal strategy for both sectors to meet their own demands, satisfy the emission reduction targets, and at the same time minimize the discounted total societal cost.

There are two ways to apply the emission constraints of the model; the first is to constrain the CO<sub>2</sub> emissions of LDV and electricity generation sectors separately, requiring each of them to satisfy their own set of annual emission constraints from 2010 to 2100. The

second is to regulate both sectors jointly, allowing them to cooperate. In the second approach, we calculate the total emissions from both sectors each year and ensure that the combined emissions do not exceed the sum of the two separate constraints for that year.

Note that the deployment of PHEVs, PHEV\_NGVs and EVs creates more electricity demand, which calls for more production from the electricity generators. The emissions coming from the extra electricity production are counted into the electricity generator side to avoid nonlinearity in the model. By implementing this relationship in the model, the LDV and the electricity generation sectors are linked together.

Next we present the linear programming formulation of the problem, define and list the inputs (sets and parameters), describe the decision variables and dependent variables, and formulate the objective function and constraints.

### 3.1. Inputs

In this section, we introduce the sets and parameters.

#### Sets

$V = \{CV, CV\_NGV, HEV, HEV\_NGV, PHEV, PHEV\_NGV, BEV\}$  = set of types of vehicles.

$G = \{C, NG, N, R\}$  = set of types of generators.

$A^V = \{0, 1, \dots, \gamma^V\}$  = age groups of vehicles on road.

$\bar{A}_g^G = \{0, 1, \dots, \bar{\gamma}_g^G - 1\}$  = extended age group of generator  $g$ , for any  $g \in G$ .

$T = \{2010, 2011, 2012, \dots, 2100\}$  = time range considered (yearly).

#### Parameters

$\gamma^V$  = maximum age group for vehicles, vehicles are grouped into 0 year old, 1 year old, ...,  $\gamma^V - 1$  year old, and equal or beyond  $\gamma^V$  year old.

$\gamma_g^G$  = lifetime length of type  $g$  generator capacity which is deployed during or after 2011, for any  $g \in G$ .

$\bar{\gamma}_g^G$  = extended lifetime length of type  $g$  generator capacity which is deployed during or before 2010, for any  $g \in G$ . We assume generator capacities built during or before 2010 possess a longer lifetime which is 1.5 times of that of generator capacities built during or after 2011, i.e.,  $\bar{\gamma}_g^G = 1.5\gamma_g^G$ . We employ this assumption to match with the input data from which there are a considerable amount of very old generator capacities (especially coal).

$c_v^{dV}$  = deployment cost of vehicle type  $v$ , for any  $v \in V$ . [\$/vehicle]

$c_g^{dG}$  = deployment cost (overnight capital cost) of generator capacity type  $g$ , for any  $g \in G$ . [\$/KW]

$c_{v,\tau,t}^{fV}$  = fuel cost of vehicle type  $v$  which is  $\tau$  year old, in year  $t$ , for any  $v \in V, \tau \in A^V, t \in T$  [\$/vehicle-year].

$c^{omV}$  = operating and maintenance (O&M) cost of a vehicle for one year of operation [\$/vehicle-year].

$c_{g,\tau,t}^{fG}$  = fuel cost of generator capacity type  $g$  which is  $\tau$  year old in year  $t$ , for any  $g \in G, \tau \in \bar{A}^G, t \in T$ . The fuel cost is incurred only when the current generator is producing [\$/kWh].

$c_g^{vomG}$  = variable O&M cost for one KW of generator capacity type  $g$  for operating for one year, for any  $g \in G$ . [\$/kWh]

$c_g^{fomG}$  = fixed O&M cost for one KW of generator capacity type  $g$  per year, for any  $g \in G$  [\$/KW-year].

$c_{v,\tau}^{r,V}$  = retirement cost of vehicle type  $v$  which is  $\tau$  year old, for any  $v \in V, \tau \in A^V$  [\$/vehicle].

$c_{g,\tau}^{rGV}$  = retirement cost of generator capacity type  $g$  which is  $\tau$  year old, for any  $g \in G, \tau \in \bar{A}^G$  [\$/KW].

$i$  = annual interest rate.

$\pi_t^V$  = survival rate of vehicles at age  $\tau$ , for any  $v \in V$ .

$d_t^V$  = vehicle total fleet size in year  $t$  which includes demand for new vehicles in year  $t$  and existing vehicles from fleet in the previous year, for any  $t \in T$  [number of vehicles].

$d_t^G$  = demand for electricity in year  $t$ , for any  $t \in T$  [kWh] We assume  $d_t^G$  includes all the electricity demand for other purposes except the need to satisfy PHEV and EV electricity consumption.

$m$  = annual amount of miles traveled by a vehicle [mile].

$k_{v,\tau,t}^V$  = reciprocal of MPG of a vehicle type  $v$ , which is  $\tau$  year old at time  $t$ , for any  $v \in V, \tau \in A^V, t \in T$  [mile/gallon].

$\bar{k}_{v,\tau,t}^V$  = reciprocal of miles per kWh of a vehicle type  $v$ , which is  $\tau$  year old at time  $t$ , for any  $v \in V, \tau \in A^V, t \in T$  [mile/kWh].

$f^V$  = amount of CO<sub>2</sub> emitted by vehicles from consuming one unit of gasoline [MT CO<sub>2</sub>/gallon].

$h_g^G$  = base case scenario of CO<sub>2</sub> amount emitted by producing one unit of electricity using generator capacity  $g$ , for any  $g \in G$  [MT CO<sub>2</sub>/kWh].

$f_{g,\tau,t}^G$  = amount of CO<sub>2</sub> emitted by producing one unit of electricity using generator capacity  $g$  which is  $\tau$  years old in year  $t$ , for any  $g \in G, \tau \in \bar{A}^G, t \in T$  [MT CO<sub>2</sub>/kWh].

$\beta_t^V$  = separate emission target for emission of the whole vehicle fleet in year  $t$ , for any  $t \in T$ . [MT CO<sub>2</sub>]. We don't set individual emission constraint for each type of vehicle.

$\beta_t^G$  = separate emission target for emission of the whole generator fleet in year  $t$ , for any  $t \in T$ . [MT CO<sub>2</sub>]. We don't set individual emission constraint for each type of generator.

$\lambda_g^G$  = usage rate of generator capacity  $g$ , for any  $g \in G$ .

$n_{v,\tau}^V$  = number of vehicles of type  $v$  which are  $\tau$  year old in the initial stock in year 2010, for any  $v \in V$ ,  $\tau \in A^V$  and  $\tau \geq 1$

$n_{g,\tau}^G$  = number of generators of type  $g$  which are  $\tau$  year old in the initial stock in year 2010, for any  $g \in G$ ,  $\tau \in \bar{A}^G$ .

$\xi$  = percentage of gasoline-driving mode for PHEV.

$\eta$  = Amount of electricity generated by hydro generation capacity per year [kWh].

### 3.2. Decision Variables and Dependent Variables

#### 3.2.1. Decision Variables

$x_{v,t}^V$  = quantity of newly deployed vehicles of type  $v$  in year  $t$ , for any  $v \in V$ ,  $t \in T$ .

$x_{g,t}^G$  = quantity of newly deployed deliverable generator capacity of type  $g$  in year  $t$ , for any  $g \in G$ ,  $t \in T$ .

$y_{v,\tau,t}^V$  = quantity of forced retired vehicles of type  $v$  of age  $\tau$  in year  $t$ , for any  $v \in V$ ,  $\tau \in A^V$ ,  $t \in T$ .

$y_{g,\tau,t}^G$  = quantity of forced retired deliverable generator capacity of type  $g$  of age  $\tau$  in year  $t$ , for any  $g \in G$ ,  $\tau \in \bar{A}^G$ ,  $t \in T$ .

#### 3.2.2. Dependent Variables

$z_{v,\tau,t}^V$  = volume of existing vehicles of type  $v$  of age  $\tau$  in year  $t$  among the stock, for any  $v \in V$ ,  $\tau \in A^V$ ,  $t \in T$ .

$z_{g,\tau,t}^G$  = existing generator capacity of type  $g$  of age  $\tau$  in year  $t$  among the stock, for any  $g \in G$ ,  $\tau \in \bar{A}^G$ ,  $t \in T$ .

$w_{v,\tau,t}^V$  = CO<sub>2</sub> emission from the vehicle type  $v$  which is  $\tau$  year old in year  $t$ , for any  $v \in V$ ,  $\tau \in A^V$ ,  $t \in T$ .

When  $\tau \geq 1$ , it represents emission from vehicle type  $v$  in the existing stock in year  $t$ , and when  $\tau = 0$ , it represents emission from the newly deployed vehicle type  $v$  in year  $t$  [MT CO<sub>2</sub>].

$w_{g,\tau,t}^G$  = CO<sub>2</sub> emission from the generator capacity type  $g$  which is  $\tau$  year old in year  $t$ , for any  $g \in G$ ,  $\tau \in \bar{A}^G$ ,  $t \in T$ .

When  $\tau \geq 1$ , it represents emission from generator capacity type  $g$  in the existing stock in year  $t$ , and when  $\tau = 0$ , it represents emission from the newly deployed generator capacity type  $g$  in year  $t$  [MT CO<sub>2</sub>].

$\tilde{w}_t^V$  = total CO<sub>2</sub> emission from vehicles in year  $t$ , for all  $t \in T$  [MT CO<sub>2</sub>].

$\tilde{w}_t^G$  = total CO<sub>2</sub> emission from generator capacities in year  $t$ , for all  $t \in T$  [MT CO<sub>2</sub>].

$d_t^{BEVG}$  = extra demand for generators from the electric driving of BEV in year  $t$ , for all  $t \in T$  [kWh].

$d_t^{PHEVG}$  = extra demand for generators from the electric driving of PHEV in year  $t$ , for all  $t \in T$  [kWh].

For year  $t \in T$  the annual electricity demand that needs to be satisfied is  $d_t^G + d_t^{BEVG} + d_t^{PHEVG}$ , thus building the linkage between the LDV and the electricity generation sectors. For simplicity we assume decision variables and dependent variables are nonnegative and continuous.

### 3.3. Objective Function

The objective is to minimize the discounted total societal cost from both sectors over the planning horizon. For each year, the costs include: the retirement cost of forcibly retired vehicles, operating cost of all vehicles in the stock, and deployment cost of deploying new vehicles, retirement cost of forcibly retired generators, operating cost of generators that are producing to satisfy demand, fixed O&M cost for operation and maintenance of generators, and deployment cost for building new generators. Note that, to guarantee one KW of deliverable generator capacity  $g$ , we actually need to build  $1/\lambda_g^G$  KW of it. Similarly, when operating one KW of deliverable generator capacity  $g$ , we need to pay the fixed O&M cost for  $1/\lambda_g^G$  KW; when forced retiring one KW of deliverable generator capacity  $g$ , we need to pay the retirement cost for  $1/\lambda_g^G$  KW. However, we only pay fuel cost and variable O&M cost for deliverable generator capacity and do not need to consider the usage rate parameter, and we assume that deliverable generator capacity work 365 days and 24 hours each day.

Therefore, the objective to minimize is

$$\begin{aligned} & \sum_{t=2011}^{2100} \left\{ \sum_{v \in V} \sum_{\tau \in A^V} c_{v,\tau}^{TV} y_{v,\tau,t}^V + \sum_{v \in V} \sum_{\tau \in A^V} (c_{v,\tau,t}^{fV} + c^{omV}) z_{v,\tau,t}^V + \right. \\ & \sum_{v \in V} c_v^{dV} x_{v,t}^V + \sum_{g \in G} \sum_{\tau \in \bar{A}^G} c_{g,\tau}^{TG} \frac{y_{g,\tau,t}^G}{\lambda_g^G} + \sum_{g \in G} \sum_{\tau \in \bar{A}^G} (c_{g,\tau,t}^{fG} + \\ & c_g^{vomG}) \times 365 \times 24 \times z_{g,\tau,t}^G + \sum_{g \in G} \sum_{\tau \in \bar{A}^G} c_g^{fomG} \frac{z_{g,\tau,t}^G}{\lambda_g^G} + \\ & \left. \sum_{g \in G} c_g^{dG} \frac{x_{g,t}^G}{\lambda_g^G} \right\} \frac{1}{(1+i)^{t-2011}} \end{aligned} \quad (1)$$

### 3.4. Constraints

#### 3.4.1. Stock Recursion

##### Vehicles

For the year 2010, the initial vehicle fleet composition is obtained from input data (Equation 2).

$$z_{v,\tau,t}^V = n_{v,\tau}^V, \text{ for any } v \in V, \tau \in A^V, t = 2010.$$

(2)

During and after year 2011, the volume of vehicle type  $v$  that is of age 0 equals the volume of vehicle type  $v$  deployed in the same year (Equation 3).