PLAUSIBILITY OF A CONVERSION-GENERATION ENERGY RECOVERY SYSTEM IN THE BOGOTÁ D.C. TRANSMILENIO TRANSPORT SYSTEM

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Abstract

This monograph explored the limits and capacities of energy recovery by testing one of the most known energy recovery systems, the automotive Regenerative Braking System on one of the biggest bus rapid transit systems in the world: The Bogotá TransMilenio. Having used an analysis of Bogotá D.C.'s energy consumption, data for two of the newest TransMilenio natural gas-powered buses, and basic thermodynamics, this monograph applied a hypothetical situation where two RBS systems, the Flywheel and the Electromagnetic system, were theoretically installed on the two buses. The energy these buses would generate even in the best of conditions, however, does not size up to one of the city's fewer demanding sectors, albeit the energy that was theoretically generated is still a decent quantity.

Keywords: Energy Recovery, RBS, KERS, TransMilenio, Energy Consumption.

Resúmen

Esta monografía exploró los límites y capacidades de la recuperación de energía al poner a prueba uno de los sistemas de recuperación más conocidos, el sistema de freno regenerativo vehicular (RBS por sus siglas en inglés), en uno de los sistemas de autobús de tránsito rápido más grande del mundo: el TransMilenio de Bogotá. Habiendo usado un análisis del consumo energético de Bogotá D.C., datos técnicos de dos de los buses a gas natural más nuevos del TransMilenio, y termodinámicas básicas, esta investigación hipotéticamente empleó una situación donde dos tipos de RBS, el de volante de inercia y el de inducción electromagnética, fueron teoréticamente instalados en los dos buses. Sin embargo, la energía que estos buses podrían generar hasta en las mejores condiciones no alcanza a uno de los sectores de menos demanda energética de la ciudad, aunque la cantidad de energía de todos modos fue una cantidad relativamente grande.

Palabras clave: Recuperación de Energía, RBS, KERS, TransMilenio, Consumo Energético.

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Introduction

This monograph was structured around the concept of energy recovery, a commonly overlooked problem in today's society. Since the industrial revolution, humanity has been too comfortable with the rapid use of materials, and has only recently begun to think about the effects of these materials' consumption. The most common case would be that of hydrocarbon fuels. These, while very useful, happen to have an extremely pollutant effect, making them bad for the planet. Not only this, they are also a non-renewable resource, and once we deplete them, the world may go through an energy shock, as there isn't any other high-energy resource we can exploit.

Recently, scientists have been researching ways to replace our use of hydrocarbons, and instead use seemingly limitless energy sources: renewable energies. Alternative energy sources like solar, wind, and hydroelectric energy are extremely good for our planet, since they only function and generate energy from seemingly limitless sources; the sun's energy is not depletable (at least not yet), and the air and water cycle that allow for wind and hydroelectric function normally without human intervention and energy usage.

Unfortunately, the reason these alternative energies seem like a dream, is because they, technically, are. While these sources of energy exist nowadays and work efficiently, they still don't generate nearly as much energy as fossil fuels do. Because of sheer population numbers in cities, and the high demand of energy of most people nowadays, it's impossible for current-day renewable energy to replace fossil fuels entirely. Eventually, it is projected that renewables will generate a lot more energy than today's fossil fuels, but that era is yet to come, and there's a need for a “bridge” between old-fashioned fossil fuels and this -dream- of renewables. (Ayres & Ayres, 2010)

And that’s where energy recovery comes in. Further explained in the following sections, energy recovery is a practice that could help society avoid the depletion of fossil fuels just in time for renewables to become the new standard. This monograph is focused on one possible use of energy recovery, that, when taken to a bigger scale, could be one of the first examples of mass energy recovery.

Justification

Energy recovery, being such an underrated concept, should be given more attention in this day and age where fossil fuels are starting to become more of a problem than a solution to industrialized production; humanity as a whole is used to consuming a lot of energy. While this itself is arguably not the problem, the real issue lies in what is happening with the waste products of this energy consumption.

This led to the investigation diving into the questions that surround earth conservation activism and its opposition to excessive fossil fuel usage nowadays; the planet's resources are limited. What can be done to stop the pollution that has been caused by releasing so much waste products into the atmosphere and hydrosphere? This question has many different answers and solutions, but none of them work individually; there isn't a single master solution to this problem, but rather, different solutions come together to form a plan.

This monograph investigation focuses on one of the proposed solutions to the problem, using energy recirculation to use less fossil fuel energy. As it was stated before, it definitely is important to think about the alternatives (i.e., renewable energies) as a step of the solution plan at a major scale, albeit not being the entire solution itself.

Finally, as it has been mentioned before, energy recovery hasn't been a topic of enough interest, and, across the years, its implementations haven't taken advantage of the entire concept of recovery and recycling. These systems would cause a bigger impact together, not only on the single owner of a car, but on the entire city, thus benefiting an entire society.

1. Objectives

1.1. General Objective

Analyze the possible implementation of an energy recovery model in the infrastructure of the public transport system of a megacity like Bogotá for its subsequent use.

1.2. Specific Objectives

- Examine the relevance of clean and self-sustaining energy in Bogotá in order to create a bigger energy efficiency.
- Characterize recovery systems that best suit the energy needs of a city like Bogotá and that can be implemented in the public transport system.
- Contrast two systems of energy recovery specialized in vehicles.
- Calculate the possible energy outputs of two vehicle recovery systems in two model vehicles and compare them.
- Compare the total energy generation of the best possible system with the most appropriate energy consumption statistic in Bogotá D.C..

2. Problem Statement

In modern society, overall energy consumption is excessive. In 2018 alone, more than 75,894 thousand barrels of oil were consumed daily to generate energy (British Petroleum Company, 2019). Humanity's current energy demand is extreme, and the way energy is generated is already becoming a problem. Not only that, this way of generating energy, like it was mentioned before, may end unexpectedly. There are more than seven billion people and only one planet to satisfy each and every individual's needs. Until current-day technology reaches utopia-like energy sources like a Dyson sphere (and even so), energy remains one of our biggest concerns.

Humanity is always looking for ways to overcome the various obstacles that they encounter as a species. And if energy is one of those concerns, that's where the question arises: can this consumption be reduced? The oversimplified answer is yes, however, it's a lot easier said than done. The attempts to save energy have been indoctrinated in society for some time, but even if this is done, it won't be enough. After all, it depends on society and every individual, making it futile on a large scale. Large impacts do not come from great progress, but from small ones on many fronts, thus achieving the solution using many different methods.

Now, a different resource-saving example is that one of plastics. Although these have been a rather revolutionary invention for today's consumer society, they are very harmful to the planet, and have caused major problems such as the so-called -garbage patch- in the Pacific Ocean. For this reason, the most acclaimed solution to the problem has been to recycle these plastics so they can be used several times in the products they constitute.

The reason this is mentioned is because of its similarity with the energy problem. While the plastic problem is a lot more difficult to solve because of its nature as a material, energy, being a purely physical *concept*, is recyclable by nature, because it cannot be created or destroyed, but rather transforms into another type of energy when it is used. The concept of energy recovery, which has been studied over the years, is to convert energy which would normally be wasted after use into a usable type of energy, such as electric, and thus reuse it for the same or a different purpose.

Following this logic, it can be said that a big enough energy recovery model could theoretically solve the problem of excessive energy expenditure (recovering a part, since excessive usage is another, merely social problem in itself). However, these systems are designed to work in fairly small systems that would not affect a community of people, let alone society. Thus, in the given example of a city, there may be a way to implement such systems, working together, to have a considerable energy recovery.

2.1. Research Question

Would it be plausible to implement a conversion-generation energy recovery system in a public transport system like Bogotá's TransMilenio?

3. Theoretical Framework

3.1. Previous Works and Background

There are many studies in energy recovery in vehicles. However, studies about its use in public transport are rare, and only one has been found to have a similar outlook to this investigation. Additionally, there are many resources and studies about the individual concepts or theories in this monograph, but not many share the same essence of energy recovery and public transport simultaneously, and even less energy recycling for different purposes.

Prof. Keith R. Pullen explains in his 2019 article “The Status and Future of Flywheel Energy Storage”, published on Joule, a Cell press scientific journal. How flywheels, and most specifically KERS (Kinetic Energy Recovery Systems, a type of energy recovery system) types can be profitable nowadays and how their future will change significantly. This article gives an insight on how KERS could change in the future and how efficient would a present implementation, theoretically, be. (Pullen, 2019)

In 2013, an article was submitted for the World Congress of Engineering. This article by R. Kapoor and C.M. Parveen compares various systems of KERS storage; mechanical, electric, hydraulic, and hydro-electric versions of the system, and analyses the properties of each. As such, the flywheel (mechanical) KERS storage seems to be the best option available, while the others are still very efficient and suitable, but not as useful. (Kapoor & Parveen, 2013)

In 2010, a book, written by Robert U. and Edward H. Ayres, which was said to be “an excerpt from another book”, explains the use of energy recycling in steel production facilities, namely Mittal Steel and Kodak, where they use the otherwise pollutant waste gases from steel production to generate electricity. The amount of energy generated by these techniques isn't exorbitant, but it is still a considerable number. The authors claim that, while conventional renewable energy like solar PV and wind turbines will eventually, indeed, become the new standard, we need a "bridge" between the now-active fossil fuel era to the future's renewable energy era, and this bridge is this recycled energy (Ayres & Ayres, 2010).

In 2014, an article for a scientific journal was produced by Štefan Hamacek, et al. explained how energy recovery, especially RBS could be used in the transport sector, specifically in the trolleybus in the Polish city of Gdynia. It is based around the analysis and simulation model of the "Monte Carlo method". Because this is a RBS energy recovery model applied to a public transport system, it is definitely a guiding point towards what this investigation will attempt to achieve. (Hamacek, et al., 2014)

3.2. Common Vehicle Auto-generation Systems

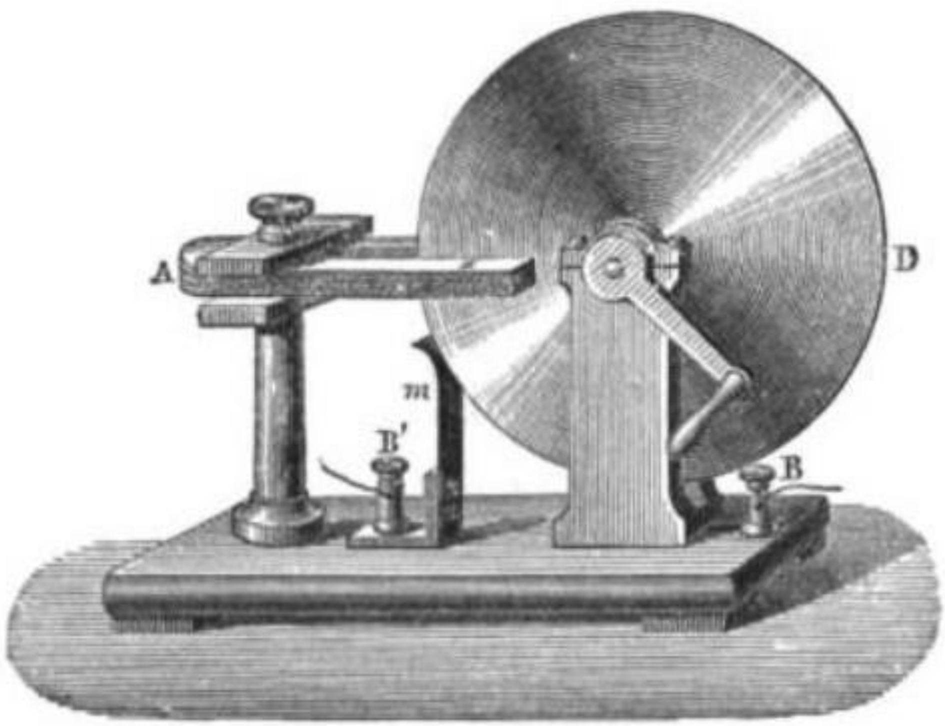
Across the years, many electrical generators have been used for vehicles, providing energy as needed for the various systems of the automobile. The first energy autogeneration systems used in vehicles were dynamos, which had the property of using electromagnetic induction (EMI), also called Faraday's law, to create an electric current from the spinning of a magnetic disk. Eventually, these were replaced by today's alternators, which create energy in a similar way, but have other advantages that make them much more viable.

Dynamos are energy autogeneration machines that produce direct current (DC) when working. As with other generator systems, they work with EMI. Dynamos were commonly used in the 19th and 20th century to generate electricity in power plants, and were then introduced to vehicles, most commonly the third-brush dynamo. Dynamos were simple in that they just had to be constantly spinning, thus generating energy uninterrupted. Such was the convenience of the

Dynamo, that today's alternators work in exactly the same way, with minor, but very drastic changes.

Figure 1

Drawing of a Faraday Disk, the First Dynamo Electric Generator.



Note. The drawing shows the main parts of the first Faraday Disk prototype. Cropped out caption and list of parts. Drawing made by (Alglave & Boulard, 1884) Alglave, É., & Boulard, J. (1884). *The Electric Light: Its History, Production, and Applications.* New York City: D. Appleton. Public Domain.

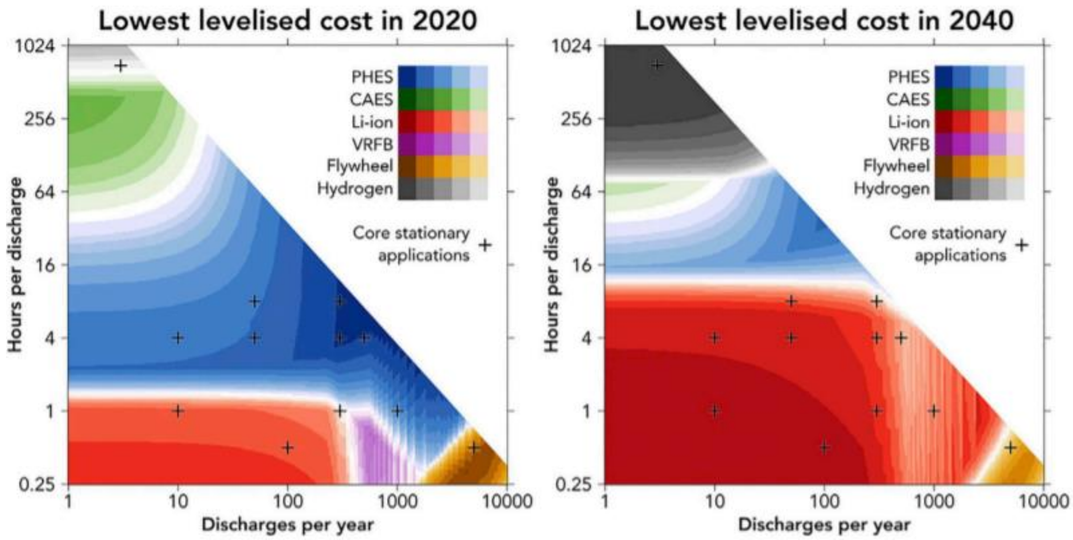
Figure 1 shows one of the first dynamo systems, the Faraday disk. Also called a homopolar generator, these such systems could generate electric current up to a million amperes under the right conditions (Valone, 1994). Faraday disks, named after Michael Faraday, were some of the first examples of applied energy autogeneration. However, as it was stated before, these devices were subsequently replaced by alternators for their use in vehicles.

Conversely, the current-day alternators became the new energy-producing standard when they overpowered the dynamos because these could produce alternating current (AC) instead of DC, hence their namesake. Alternating current is highly preferred because of a wide variety of reasons, so naturally the alternators replaced the dynamos for the most part. Both systems work practically in the same way, and using the same principle of electromagnetic induction. While dynamos were used for energy generation in most vehicles, by then, some particular vehicles, especially those that needed a great amount of electrical power for radio transmission and other devices, such as ambulances, did use alternators.

Nowadays, in almost any car, at least one alternator is used to generate electricity for the vehicle's many electric systems. This is normally enough for a regular gasoline-powered automobile because the gasoline fuel is enough for the car to move, while electricity takes care of other aspects like the ignition of the gasoline, the internal computer and safety systems of the car, and others, which don't require a great power input. However, EVs (Electric Vehicles) and hybrid cars depend on electricity to move, so they need a lot more electric power. Of course, this means that these cars have bigger and better batteries, better alternators, and other such systems.

Figure 2

Lowest Levelized Cost of Storage



Note. 2020 and 2040 prediction of the different types of batteries and their hours per discharge, and their discharges per year. Reproduced from (Pullen, 2019) Pullen, K. R. (2019). The Status and Future of Flywheel Energy Storage. Joule, 3(6), 1394-1399. doi: https://doi.org/10.1016/j.joule.2019.04.006.

However, as seen in Figure 2, hydrocarbon fuels, because of their explosive power, are more efficient in providing energy for a moving vehicle using a four-cycle combustion engine than electric power, because of Li-Ion limitations. This means that, while EVs and hybrids do have a lot of power in them, they're at a relatively higher risk of depleting their batteries while on a drive, and need to be recharged significantly more often. A solution for this has been energy recovery, which is explained in the following section.

3.3. Vehicle Energy Recovery Systems

Energy recovery is used in a wide range of vehicles, but almost exclusively in hybrids and electrics because of the reasons stated above. There are many energy recovery systems for these vehicles, but the most effective as of now are Regenerative Braking Systems, or RBS.

To make this section clear, it is necessary to explain the law of conservation of energy. This law, also called the 0^{th} law of thermodynamics, dictates that energy cannot be created, or destroyed. While it is still unknown if the expansion of the universe is still generating new energy, the observable universe has a fixed amount of energy that humans can use. As such, any energy that has been present in earth since the beginning of time is still in the earth, just having been converted to different types of energy.

RBS work under a very simple concept: use the energy that would normally be wasted by braking, and convert it to usable energy for further use. When cars without RBS brake, all of the kinetic energy that the car has will be wasted as heat energy in the brake disks. This has been the case for about any brake in any vehicle, until RBS arrived. According to the law of conservation of energy, the energy that is "lost" during braking can be recovered instead of wasted as heat. RBS do this by employing different systems that can brake a wheel while also keeping the energy for future use. Furthermore, an RBSs normally doesn't brake the car entirely by itself, but helps itself with the conventional brakes if the speed is too high. (Bhandari, et al., 2017)

RBS have many advantages and disadvantages, inclined mostly to the former. Its main advantage is the fact that, being an energy recovery system, it increases the total efficiency of any vehicle that uses them for their own gain. That means that electric vehicles, under certain conditions, will benefit greatly from the energy boost that RBS provide. This also means that, indirectly, RBS contribute to the planet by saving up on electricity, which is normally generated using fossil fuels. Of course, this advantage can be attributed to energy recovery as a whole, and not just RBS. On the other hand, RBS also have some disadvantages, mainly for the vehicle, as Bhandari et al. (2017) state:

> "The main limitation of regenerative brakes when compared with dynamic brakes is the need to closely match the electricity generated with the supply. With DC supplies this requires the voltage to be closely controlled and it is only with the development of power electronics that it has been possible with AC supplies where the supply frequency must also be matched (this mainly applies to locomotives where an AC supply is rectified for DC motors). [2.] Regenerative braking is necessarily limited when the batteries are fully charged. Because the additional charge from regenerative braking would cause the voltage of a full battery to rise above a safe level, our motor controller will limit regenerative braking torque in this case. 3. Increases the total weight of vehicle by around 25-30 Kilograms." (Bhandari, et al., 2017)

Regenerative brakes come in many different forms; each usually being used for a different kind of car. Formula One cars, for example, have been some of the staple uses for the KERS, or Kinetic Energy Recovery System. Consumer EVs use regular RBS, which have branched in many types. Technically, the KERS is a subtype of RBS used mostly for racing cars.

There are roughly 5 types of RBS, each having its own advantages, but the most used ones, and the ones this investigation will focus on, are the Flywheel and Electromagnetic RBS. In the Flywheel RBS (further abbreviated FRBS), the energy is stored mechanically in a flywheel that operates independently from the wheels of the vehicle. In the Electromagnetic RBS (further abbreviated ERBS), the drive shaft of the vehicle is attached to an electric generator, which, when active, will slow down the drive shaft and eventually bring it to a halt.

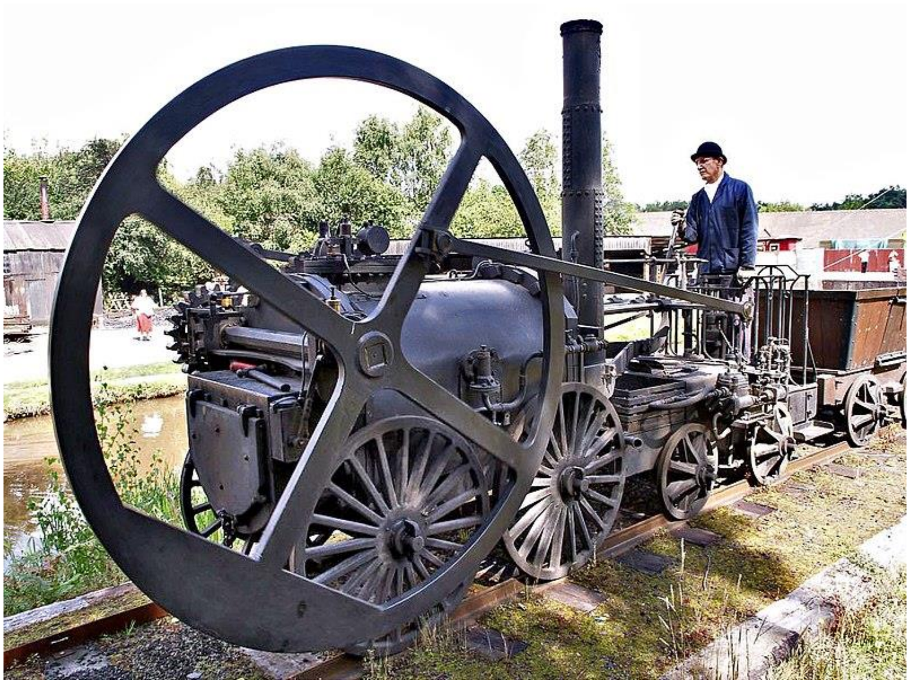
The following sections characterize the FRBS and ERBS, showcasing how they would be implemented in a vehicle.

3.3.1. Flywheel RBS

Flywheels are mechanical devices used to store mechanical energy. As their name implies, they're wheels that move independently from the rest of the system. Such devices have been used a lot for energy storage in many devices.

Figure 3

Richard Trevithick's 1802 Steam Locomotive.

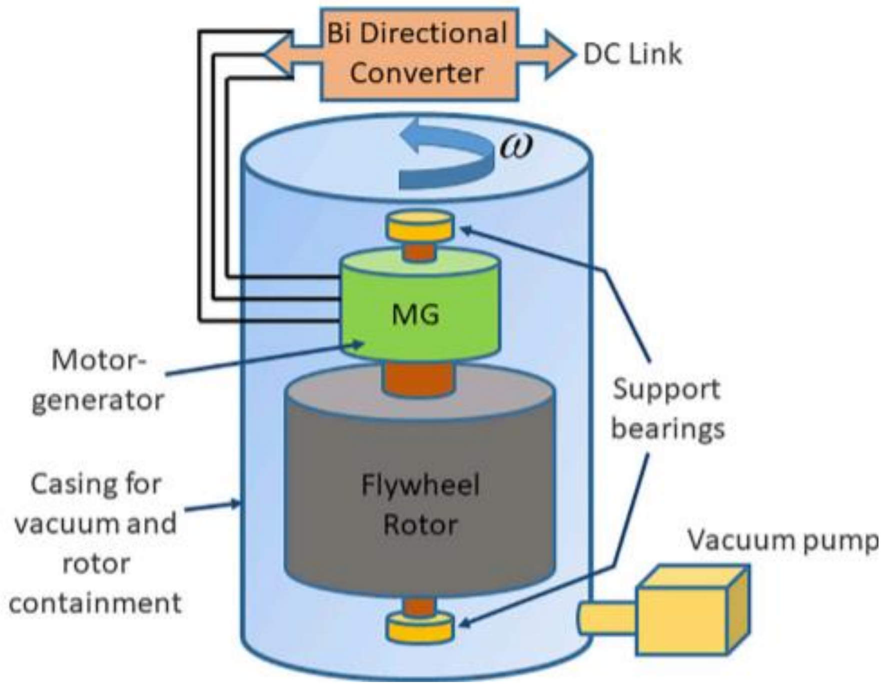


Note. A picture of Richard Trevithick's 1802 Steam Locomotive, which used a flywheel to transfer energy from its main and only cylinder to the rest of the system. Taken from Birmingham Museums Trust, (2005). *Richard Trevithick's 1802 steam locomotive.* [Online Image]. Wikimedia Commons. CC BY-SA 4.0.

Figure 3 depicts a flywheel, used in Richard Trevithick's locomotive. Although it had a different use from flywheels in FRBS, its function was the same; store mechanical energy. Flywheels in FRBS store the kinetic energy that the car loses when it brakes, and then converts it to electrical energy, using a motor-generator. To maximize efficiency, FRBS flywheels are stored inside a vacuum chamber, to prevent friction from air particles, and thus losing the least energy possible.

Figure 4

A Flywheel System Configured for Electrical Storage



Note. Diagram of a flywheel system used to store electrical energy. Reproduced from Amiryar and Pullen. (Pullen, 2019) Pullen, K. R. (2019). The Status and Future of Flywheel Energy Storage. Joule, 3(6), 1394-1399. doi: https://doi.org/10.1016/j.joule.2019.04.006.

Figure 4 shows the diagram of a conventional Flywheel Energy Storage System. The output current varies, but in vehicles, it’s normally AC. The flywheel is usually rather heavy so it keeps its inertia without any interruptions.

There are two versions of FRBS, the KERS, which is normally used in Formula One, and the automatic FRBS, which is used in some consumer EVs. KERS are activated by pushing a button, which gives the engine a boost using the electricity stored in the battery, previously obtained from braking (Racecar Engineering, 2009). Of course, Formula One cars are made to reach very high speeds, reaching around 220km/h at median (STATS F1, n.d.) for racing tournaments, and as such, they're not designed to be braking very often, and even less to brake to a full stop (only in certain cases, like wheel replacement), and also, because most of the sport is based around the pilots' expertise, not the cars, the pilots are the ones who decide when and where the car accelerates, so a manual -KERS powered turbo button- is fitting for the sport.

The main difference between a KERS and a regular RBS is the usage of energy. KERS, being used in motorsport, normally recover the energy from braking and use it to boost acceleration. The energy stored in the flywheel is then used for acceleration again so the car does not lose speed. RBS, on the other hand, is different in that it normally recovers energy and stores it for the further use of the vehicle. The difference is, then, that the KERS stores energy very shortly, and uses it almost exclusively for acceleration boost (hence why F1 KERS were activated with a button), and instead, the RBS supplies the energy back to the main battery as a recycling measure.

In both cases, the FRBS usually is equipped with a separate transmission gearbox, which attempts to keep the flywheel spinning the whole time, changing gears so the flywheel can't decelerate.

Conversely from racing cars, EVs and hybrids are normally driven around in urban areas, which require a lot of braking, mainly in stoplights, and traffic jams. Because of this, the automatic system is more suited for these, for the driver doesn't have to worry about wanting extra speed like in racing, but rather, they just need better mileage and more power in the car's batteries.

However, consumer EVs and Hybrids normally don't use FRBS, because, as it was stated before, these don't reach the high speeds that Formula One cars normally do. As such, FRBS rarely, if ever, get used for consumer vehicles.

This investigation will use the GKN Gyrodrive KERS's flywheel as a reference point. This FRBS was specifically designed for buses, that store a lot of energy that comes not from their velocity, but from their mass.

> "The motor/flywheel can spin at speeds up to 45,000 rpm, although in the bus application speeds are generally in the 16,000- to 36,000-rpm range. The motor/flywheel is designed to be fitted under a passenger seat in the bus, so passenger capacity is not affected. The electronic control system is mounted under a second passenger seat. Altogether the system weighs 300 kg (660 lb.), according to Reinartz. […] The operating voltage is 500 V and energy storage is in the 1.2- to 1.8-MJ range, with a power rating of 120 kW. The weight of the motor/flywheel unit is around 60 kg. It's not just the weight of the aluminum housing and the carbon composite, but there's obviously copper in there, too." (Kendall, 2015)

In a system where the flywheel acts as a brake (recovering the kinetic energy that would normally be lost to friction), the flywheel's energy can be expressed as the same kinetic energy of the vehicle before braking:

$$\frac{mv^2}{2} = RKE_{fly}$$

Where *m* is the mass of the vehicle, and *v* is the initial velocity of the vehicle just before braking (Rahane & Varpe, 2016). This is the total rotational energy that will be stored in the flywheel, for a time short enough to not take friction into account (for longer times, internal friction decreases the energy over time). Now, the conversion to electrical energy is another problem in and on itself, suffering from heat energy loss, but recovering a great percentage of the energy nonetheless. Because a regular MG will be used, the equation for it is rather similar to the one used in the ERBS which is mentioned further below.

Normally, calculations for the recovered energy of a flywheel need its efficiency. The normal efficiency for a flywheel storage system MG is around 85% (Pullen, 2019). Along with this data, the total amount of recovered energy is then:

$$EE = \eta_{gen} RKE_{fly}$$

Where *EE* is electrical energy in Joules, η_{gen} is the efficiency of the generator in percentage, and RKE_{fly} the rotary kinetic energy of the flywheel in Joules.

On the other hand, according to Prof. Pullen (2019), a flywheel can certainly recover energy efficiently, but its storage and intake are an entirely different issue. A regular flywheel uses a motor-generator to convert the residual kinetic energy to electric energy. However, the materials used in these MGs and their grid-tied inverter could be better, and aren't working in optimal conditions.

> "It is immediately apparent that the power cost is dominated by the MGPE cost, not the flywheel, so cost reductions here have the greatest impact. The greatest potential is developments in power electronics with higher voltage metal-oxide-semiconductor field-effect transistor (MOSFET) leading to reduced costs and lower losses." (Pullen, 2019)

Nevertheless, the amount of energy stored by a Lithium-Ion battery and the time it takes to discharge will be improving in the following years as predicted by the studies of Prof. Pullen shown in Figure 2. A flywheel can discharge and charge a vast number of times because of its mechanical nature; however, it can't keep the charge for long, and that's Li-Ion batteries are much more preferred.

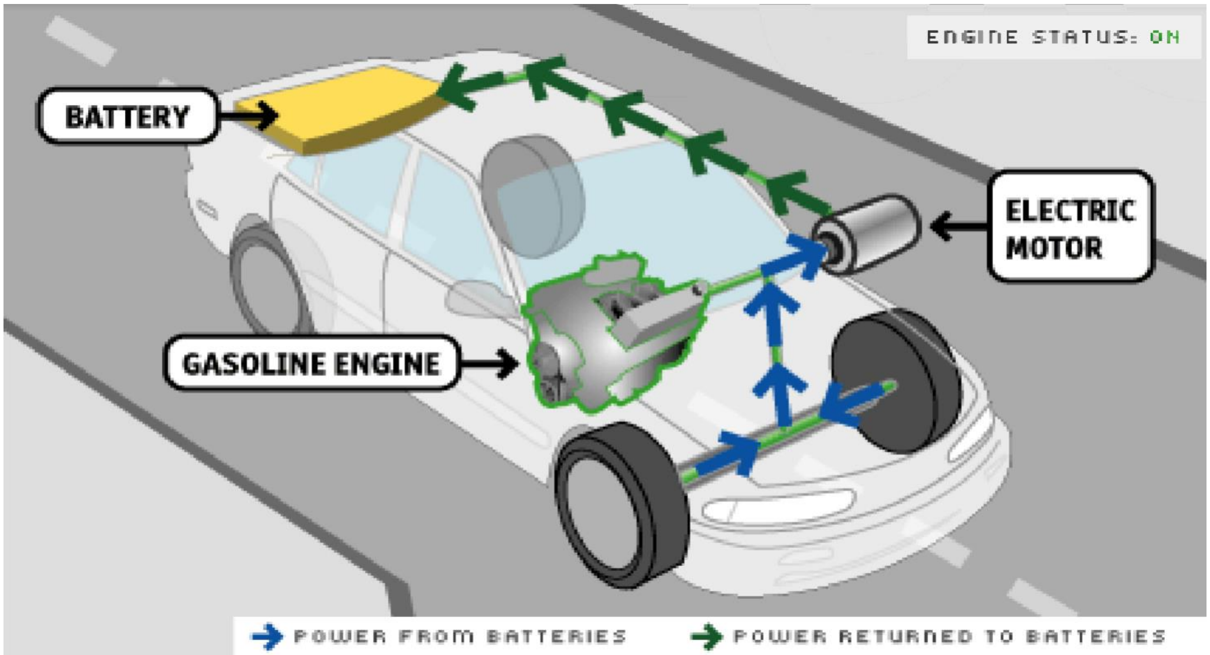
This means that the FRBS today may still have some faults because of the reasons mentioned above. However, its regenerative brake potential is still not something to be underestimated. Following this principle, while the FRBS can be improved, it remains a solid candidate to the objective this investigation is aiming to achieve, for the Rapid Transit Buses presented in the investigation hold enough of a mass for the FRBS to work, if it can be installed, albeit, not used as a KERS, but as a FRBS.

3.3.2. Electromagnetic RBS

Electromagnetic RBS systems depend on the drive shaft of a vehicle. The motor, which normally would spin the wheels in order for the car to move, turns into an electric motor which will slow down the wheels applying friction and generating energy in the process. In the case of hybrid vehicles, like the one shown in Figure 5 below, have an electric motor added on top of the normal fuel engine for the same purpose as a fully electric ERBS.

Figure 5

Motor-Generator RBS in a Hybrid EV



Note. Diagram of a Motor-Generator Regenerative Braking System. Adapted from (Bhandari, et al., 2017). Bhandari, P., Dubey, S., Kandu, S., & Deshbhratar, R. (2017, February). Regenerative Braking Systems (RBS). International Journal of Scientific & Engineering Research, 8(2), 71-74.

ERBS stores its energy in a Li-Ion battery under normal conditions. This type of RBS is used in some racing cars, namely Le Mans models. One such example is the Porsche 919 Hybrid, which uses an ERBS to feed the electric motor On-Demand.

> "During braking, a generator at the front axle converts the car's kinetic energy into electrical energy. In the split exhaust system, one turbine drives the turbocharger while another converts surplus energy into electrical energy. The braking energy contributes 60 per cent, with the remaining 40 per cent coming from exhaust gas. The recuperated electrical energy is stored temporarily in a lithium-ion battery and feeds an electric motor on demand. "On demand" means: the driver wants to accelerate and calls up the energy at the press of a button. In accordance with the latest regulation changes, the power from the

> combustion engine is just under 368 kW (500 HP), and the output from the electric motor is well over 294 kW (400 HP).” (Porsche, 2016, par. 3)

ERBS are also the most used RBSs for consumer EVs and hybrids. These can brake the movement of a car in urban conditions without any problems. The energy generated from an ERBS’s recovery feature is around 10% of the maximum energy of the vehicle, under certain conditions. (Folkson, 2014)

Additionally, there are two types of ERBS, the parallel and the serial. The serial type employs regular friction-type brakes, and also adds the regenerative brake. The main feature of the serial system is an integrated control strategy, where the brake torque is automatically adjusted by the brake pedal as the driver presses it. This system can only operate on a brake-by-wire system. Parallel, on the other hand, does not posses the integrated control strategy the serial does, employing the RBS and friction brake system in parallel. Instead of checking the pedal, the parallel system takes into account the battery charge, the velocity of the vehicle, and the motor capacity. The best option is the serial, which can save up to 30% in fuel efficiency, in contrast to the parallel’s 18%. (Varocky, 2011)

For this investigation, it will be assumed that the efficiency of the motor generator is 90%, as it is normal in many MGs used for Regenerative Braking (Toll, 2018).

As it was mentioned previously in the FRBS section, the energy converts from kinetic to electric, and the same kinetic energy equation applies, albeit this time the energy will not be rotational. In this case, it will be converted to chemical as well. Skipping ahead to the equation when both eficiencies are known, the total produced electrical energy by the ERBS is:

$$W_{out} = \eta_{gen}\eta_{batt}KE_{vehicle}$$

In Joules. This equation outputs work, instead of energy, but because in this case Work is not a vectorial quantity, energy can be used instead (Kinetic energy is calculated with speed, not vectorial velocity).

3.4. TransMilenio Bus Rapid Transit System Specifications

The TransMilenio is Bogotá's (and neighboring) Bus Rapid Transit (BRT) system. It entered operation ever since December of 2000, and has remained the official public transport system for the city.

The Transmilenio consists of 8 main lines of bus routes that run from the neighboring municipality of Soacha, throughout the entire city outskirts and centre, all the way to the northern street 194, called Terminal Station. The system covers a total of 114.4km (TransMilenio S.A., 2020) and operates for the most part of the day. It's divided in three subservices:

- The express route, which only stop at certain stations in one route.
- The easy route, which stops at every single station in the lane.
- The dual route, which is similar to the express, but also stop on non-main stations (regular bus stops). (TransMilenio S.A., 2020)

Additionally, The system is divided in 6 subsystems:

- The Trunk (Troncál) line, composed of the bigger articulated and biarticulated buses. These have designated stations and follow specific routes. They're equipped with many features such as hydraulic doors, accesibility systems such as speakers and LED panels, and a couple others. These buses have an average capacity of 250-270 passengers (TransMilenio S.A., 2018), and are equipped with benches and wheelchair spots for commodity and accesibility.

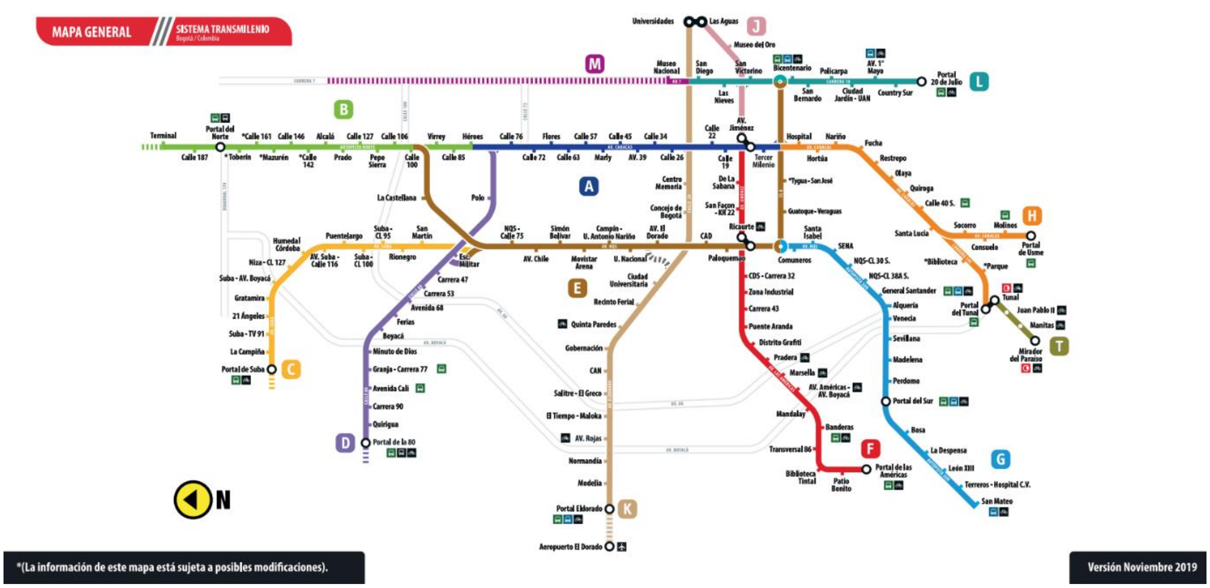
- The Feeder (Alimentadores) line, composed of smaller, regular buses who transit on the normal highways and roads as regular civilian vehicles. These pick up passengers at designated locations that are too far off a main station, and transport them directly there (for portal stations) or close to (for minor stations). These buses are also equipped with benches and accesibility features, and have a maximum capacity of 90 people.
- The Urban (Urbano), Complementary (Complementario), and Special (Especial) subsystems are composed of regular buses. Similar to the feeder system, these pick up passengers in bus stations and transport them closer to the stations.
  - The urban system is different from the other two in that, like a feeder, it travels around the city getting passengers closer to stations, and it travels the most important areas of the city, like highways. Also, it is different from the feeder because the latter transports users from and to certain zones as well, and is more expanded overall, unlike the urban, which is designed to be more like a "quick hop" to a trunk system.
  - The complementary system is different from the other two in that its buses are assigned to different zones, municipalities and locations in the city, and transport users to a station. These are usually operated by private companies which have signed a contract with the TransMilenio administration to sport its image and be allowed to use its routes.
  - Finally, the special system is different from the other two in that it only goes from station to station. Much like a trunk system, special buses usually transport passengers through the regular highways between bigger stations like portals or terminals.

- The TransmiCable subsystem, unlike the rest, is composed of a gondola system, and it's used mainly to provide access to many elevated zones in the Ciudad Bolívar district. It connects directly with a trunk station, and some urban stations.

The Trunk system, as it was stated before, is run by articulated and biarticulated buses, which feed on diesel and natural gas. The buses have been provided by many different countries over the years, namely Marcopolo S.A., Mercedes-Benz AG, AB Volvo and, most recently, AB Scania. The majority of these buses have been articulated, which means that it's divided in two rigid sections, connected by a single pivoting joint, in order to let the bus make turns safely. Biarticulated buses work in the exact same way, except having another pivoting joint, thus extending the size of the bus slightly.

Figure 6

Map of the Transmilenio Trunk Service



Note. November 2019 map of the Transmilenio trunk routes across Bogotá. Reproduced from (TransMilenio S.A., 2020) TransMilenio S.A. (2020, September 26). Mi Plan de Viaje. Guía de Servicios - Sistema Transmilenio. Bogotá: TransMilenio S.A.

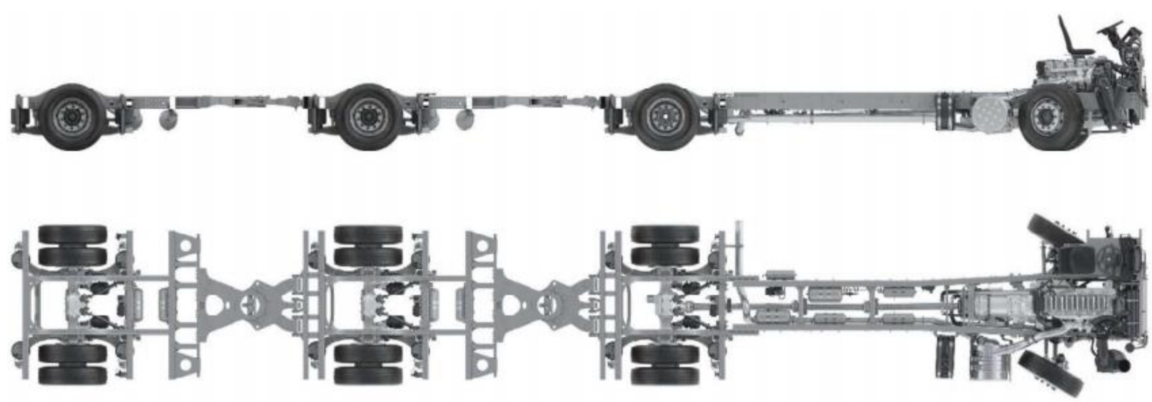
The shortest possible complete route is that one of the B55 express route, which only stops in 3 stations. The longest possible route is the 8th easy route, covering 33 stations in one go.

This investigation will be based around the two newest bus types, the Scania F340 HA 8x2 biarticulated bus, and the Scania K320 IA 6x2/2, which are detailed in the following sections.

3.4.1. Scania F340 Biarticulated

Figure 7

Diagram of Scania F340 Chassis



Note. Chassis of the Scania F340 from the side and from above. Reproduced from (Scania Colombia S.A.S., 2020). Scania Colombia S.A.S. (2020, October 6). *Cotización Scania F340 HA 8x2 Euro 6 Bi-articulado a Gas de Piso Normal.* Bogotá.

The Scania F340 is the most recent biarticulated bus that the TransMilenio began using around the first half of 2019. It is one of the only buses that don't use diesel as its fuel, but instead, uses natural gas. It has a capacity of 250 passengers.

Figure 7 shows the chassis of the F340. It is apparent from the diagram that the bus posseses 4 axes. These can be slightly modified to add a FRBS, or, instead, the drivetrain adapted to a ERBS in the 2 axes in the front.

The F340’s brakes are pneumatic, which means that compressed gas is used to create pression on a brake pad. EBS and ABS are also installed in the vehicle. EBS, or Brake-By-Wire systems (although EBS is short for Electronic Braking System) are capable of braking different wheels via an electric impulse. EBS is operational in the majority of EVs and hybrids, so it is compatible with RBSs. Conversely, ABS, or Antilock Braking System, is a system present in most modern vehicles like automobiles, motorcycles, buses, and even certain aircraft. It prevents the tyre from blocking completely in a surface, thus increasing maneuverability.

On the other hand, the F340 also has a mechanical retarder installed in its gearbox. A retarder is a device that slows the vehicle slowly, so that it doesn’t go out of control in steep surfaces. This, of course, means that the engine also features engine brake, slowing the vehicle down when the accelerator isn’t pressed, and the vehicle is running in lower gears like first or second.

Other details that are not as important but cannot be overlooked are:

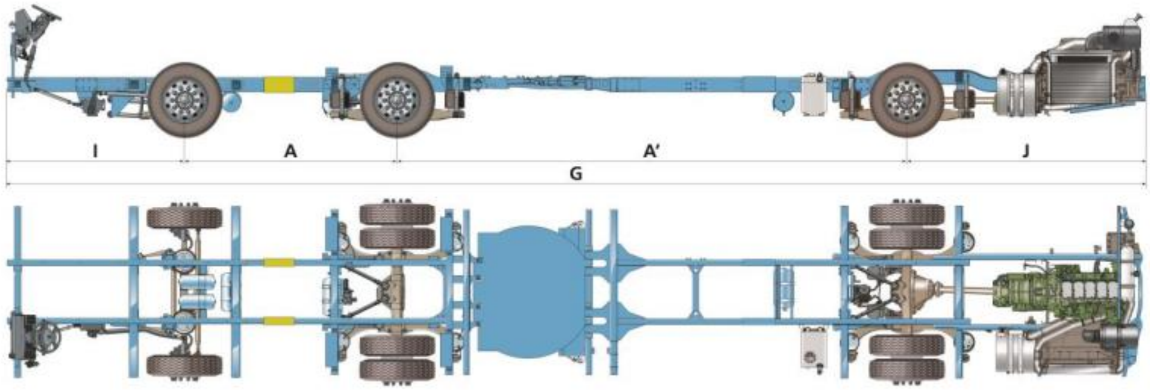
- The F340’s engine is a natural gas engine with 5 cylinders. It is compliant with the Euro 6 carbon emission standard.
- The gearbox features 7 velocities: First to sixth and reverse.
- The F340 uses steel rims.
- The F340 features suspension in all but one axes, the ones at the back having a 12000kg resistance, and the one at the front 7500kg. (Scania Colombia S.A.S., 2020)

3.4.2. Scania K320 Articulated

The Scania K320 is the other most recent bus for the trunk subsystem. It was introduced at the same time as the F340. It has a capacity of 160 passengers.

Figure 8

Diagram of Scania K320 Chassis



Note. Chassis of the Scania K320 from the side and from above. Reproduced from (Scania Colombia S.A.S., 2018). Scania Colombia S.A.S. (2018, January). *Especificación Técnica K320.*

The chassis diagram is presented in Figure 8. This bus has one less axis, only comprising 3 of them, of which one uses a single wheel. This vehicle's motor is actually in the back of the bus, as it is shown in "J" in the diagram.

Just like the F340, the K320 also has ABS and EBS. Its brakes are more or less the same. Also, one of the brake modes involves braking with all axes to create a faster brake.

Only the wheels in the back are connected via a drive shaft. This means that if an ERBS were to be installed, it'd only work with the back axis.

Other important details are:

- The K320's gas engine has 5 cylinders. It is compliant with the Euro 6 carbon emission standard, like the F340.
- The gearbox is automatic, something rather uncommon for big vehicles. It also incorporates a retarder.
- All axes have a suspension system. The front one has 7500kg of resistance, the middle one 10230kg, and the rear 12000kg. (Scania Colombia S.A.S., 2018)

3.5. Bogotá's Electricity Consumption

Bogotá D.C. is the capital of Colombia, and its biggest city with the biggest number of inhabitants, 7,412,566 in 2018. (DANE, 2018) Being the country's center and most populated city, it is (sometimes) considered a megacity. As such, this city is one of the biggest electricity consumers in the country.

The following table (Table 1) and graph (Figure 9) shows the electric energy consumption in Bogotá between 2000 and 2012, in GWh (Gigawatt hours).

Table 1

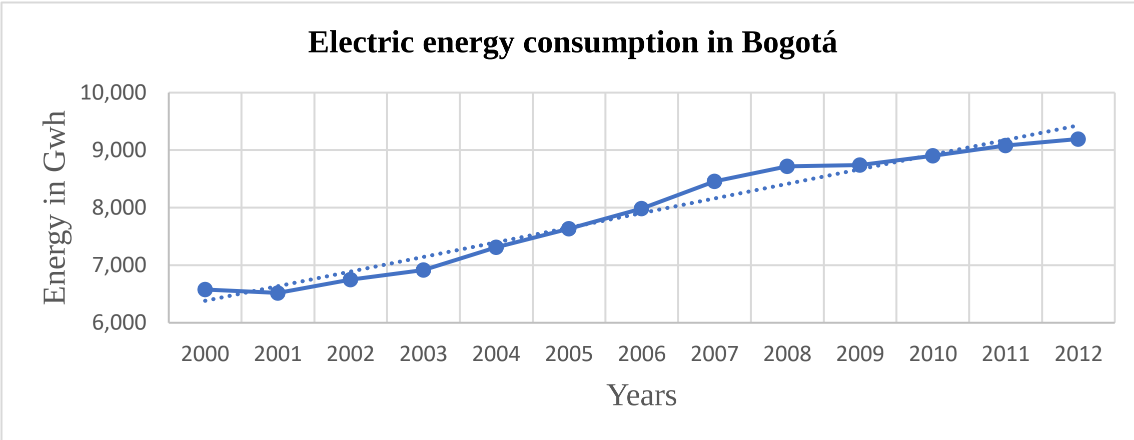
Electric Energy Consumption in the Capital Region from 2000 to 2012 in GWh.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Bogotá Total	6,575	6,519	6,751	6,918	7,311	7,634	7,983	8,455	8,719	8,743	8,901	9,081	9,194
Residential	2,993	3,010	3,054	3,099	3,163	3,255	3,334	3,426	3,572	3,609	3,650	3,692	3,699
Commercial	1,303	1,303	1,472	1,561	1,727	1,904	2,123	2,399	2,498	2,603	2,687	2,798	2,911
Industrial	1,602	1,527	1,610	1,669	1,843	1,925	2,011	2,117	2,106	1,981	2,011	2,055	2,050
Official	426	422	362	363	352	326	315	309	335	339	340	320	317
Street lighting	251	257	252	226	225	223	200	204	208	212	213	216	218

Note. Table showing the total energy consumption in Bogotá's different energy usage sectors. Reproduced from (Martínez, et al., 2013, p. 101). Martínez, A., Afanador, E., Zapata, J. G., Núñez, J., Ramírez, R., Yepes, T., & Garzón, J. C. (2013, Julio). Análisis de la situación energética de Bogotá y Cundinamarca. Fundación para la Educación Superior y el Desarrollo. Extra information cropped out.

Figure 9

Graph of the Electric Energy Consumption in Bogotá from 2000 to 2012.



Note. Own work, taken from (Martínez, et al., 2013) Martínez, A., Afanador, E., Zapata, J. G., Núñez, J., Ramírez, R., Yepes, T., & Garzón, J. C. (2013, Julio). *Análisis de la situación energética de Bogotá y Cundinamarca.* Fundación para la Educación Superior y el Desarrollo.

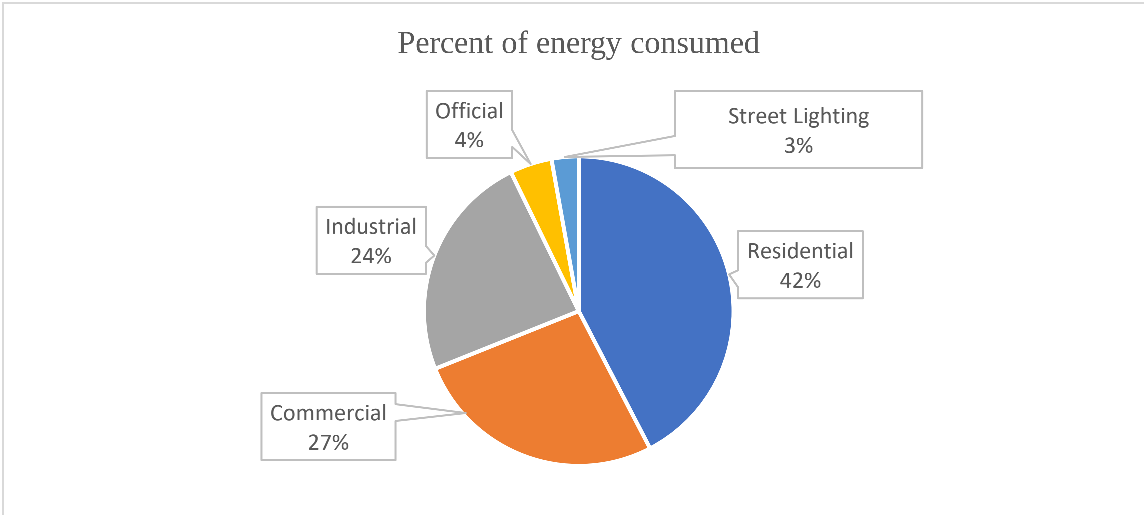
While this data is not up to date, it is possible to calculate an average consumption of energy with population data in 2020.

Table 1 shows that the total consumption has been increasing around a thousand GWh every 3 or more years, showing a relatively constant increase. To further support this, Figure 9 demonstrates that the growth trend is fairly linear.

It is also possible to create a percent pie chart from Table 1, which could give an approximate, visual representation of the percent certain sectors use. This will be Figure 10. Additionally, the same table states that Cundinamarca's total consumption for 2012 was 3.265GWh, and its Official and Street Lighting values added are 81GWh. This value is important for later explanations. (Martínez, et al., 2013)

Figure 10

Percent of Energy Consumed per Sector in Bogotá from 2000 to 2012.



Note. Own Work, taken from (Martínez, et al., 2013) Martínez, A., Afanador, E., Zapata, J. G., Núñez, J., Ramírez, R., Yepes, T., & Garzón, J. C. (2013, Julio). *Análisis de la situación energética de Bogotá y Cundinamarca.* Fundación para la Educación Superior y el Desarrollo.

Figure 10 was calculated with the average consumption of every year from 2000 to 2013. It clearly demonstrates how the residential sector consumes a significantly higher amount of energy than the other sectors, and how the street lighting and official sectors consumes very little compared to the others.

As for the current date, Martínez et al. (2013) make predictions in their study, and develop a formula to calculate the energy consumption all the way to 2020. Unfortunately, Codensa and the government haven't published any new accurate reports of sectorial energy consumption to date. While the following data may be inaccurate, it has been calculated using a complex set of equations that take into account many factors, and, associated with the population change, are very accurate. (See Annex 1)

This prediction calculation returns very precise data that, while speculated, is still very trustworthy. The predicted data is shown in the following table (Table 2):

Table 2

Result of Energy Projections for the Region – Base Scenario

Year	**Aggregated Model**		**Sectorial Model**		**UPME**	
	GWh	Growth %	GWh	Growth %	GWh	Growth %
2013	14.508	4,1	14.363	3	14.720	5,6
2014	15.083	4	14.895	3,7	15.207	3,3
2015	15.685	4	15.453	3,7	15.739	3,5
2016	16.297	3,9	16.031	3,7	16.801	6,7
2017	16.959	4,1	16.645	3,8	17.547	4,4
2018	17.618	3,9	17.267	3,7	18.316	4,4
2019	18.275	3,7	17.896	3,6	19.075	4,1
2020	19.024	4,1	18.583	3,8	19.674	3,1

Note. Results of a prediction of the amount of energy used in the capital region from 2013 to 2020. Reproduced from (Martínez, et al., 2013, p. 147). Martínez, A., Afanador, E., Zapata, J. G., Núñez, J., Ramírez, R., Yepes, T., & Garzón, J. C. (2013, Julio). *Análisis de la situación energética de Bogotá y Cundinamarca.* Fundación para la Educación Superior y el Desarrollo.

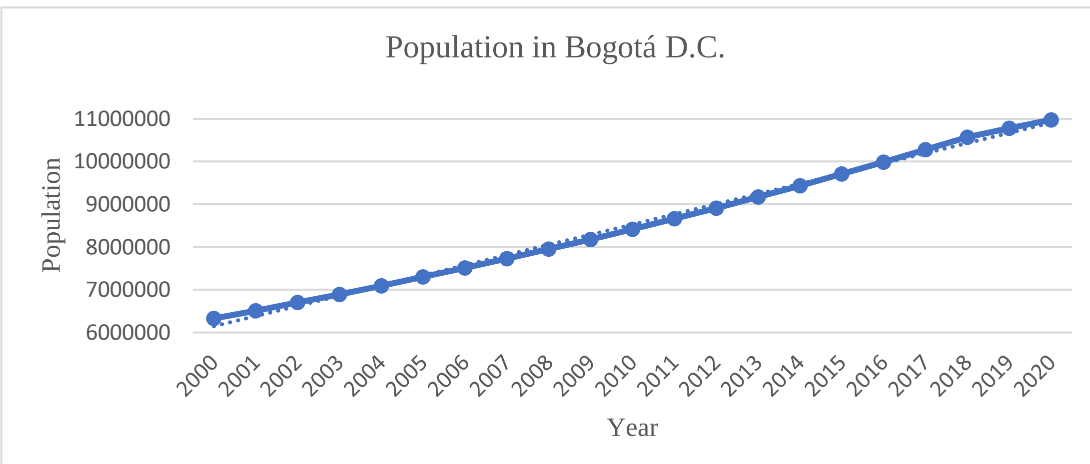
As expected, the total energy consumption for 2020 is around 18,000 to 20,000 GWh. This result is also compared with the UPME's (Miner-Energetic Planning Unit, English for Unidad de Planeación Minero Energética) calculations. Both Martínez et al. and the UPME agree on a relatively close number. An average calculated value between the 3 pieces of final data for 2020 would be 19.093 GWh for the whole region, a table not included in the document (See Annex 1).

Additionally, according to Martínez et al. (2013, p. 147), this table only takes Bogotá and Cundinamarca into account. This means that the table adds the values of both regions and makes this the final aggregated value. Also, this value disregards the “Official” and “Street Lighting” values. (Martínez, et al., 2013, p. 145)

The increase in population of Bogotá is also relatively lineal, having actually decreased growth rate near 2019. The following chart describes the change in population from the year 2000 to the year 2020.

Figure 11

Population of Bogotá D.C from 2000 to 2020.



Note. Graph with trend line representing the total population of the city of Bogotá D.C. from the year 2000 to 2020. Own work taken from (United Nations, Department of Economic and Social Affairs, Population Division, 2019 as cited in Macrotrends LLC, 2020) United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World Population Prospects 2019: Data Booklet.* United Nations., Macrotrends LLC. (2020, October). *Bogota, Colombia Metro Area Population 1950-2020*. Retrieved from Macrotrends: https://www.macrotrends.net/cities/20837/bogota/population.

As such, it is possible to approve of the accuracy of Martínez et al.'s research, considering the data accurate, even though it may not be factually proven.

4. Methodological Framework

This monograph is classified as an investigative type, according to (Colegio San José, 2020), where the main objective was to analyze and characterize energy recovery systems in order to link their pertinence to an already existing transport system. As such, the analysis attempted to prove this aforementioned pertinence on both bus types detailed in the theoretical framework.

The investigation was of a documental type, once again, according to (Colegio San José, 2020). It is documental because, having gathered the information on RBS types, the TransMilenio system, and energy consumption data, it was analyzed in the documental analysis in order to reach a certain conclusion.

This monograph was of a mixed research focus. Most of the research and investigative work is based on a quantitative focus, where the analysis of data and statistics makes up the majority of the analysis. However, a qualitative focus was also slightly applied, in terms of the social aspect and impact of the main objective.

The analysis was executed with certain mathematical equations and calculations of the potential energy production that an RBS system could produce on certain TransMilenio trunk routes, thus producing results with medium accuracy. While these results were, indeed, approximate and very far from exact, they were still enough of a data source to compare it to the previously analyzed energy expenditure report, and produce a conclusion and answer to the problem question stated at the beginning of the monograph.

Most of the information gathered to investigate the subject and analyze it afterwards was gathered from various repositories and scientifical journals specific to energy, mechanical, chemical and electrical engineering available on the internet. Other sources of information, such as books, were collected from internet libraries as well. Some other specific sources, like the specifications for the buses, were provided by TransMilenio officials.

5. Documental Analysis

This analysis will be a recollection of the analysed data presented on the theoretical framework, along with a number of calculations and comparisons, following the objectives presented above.

5.1. Relevance Of Clean Energy In Bogotá

As it was stated in the theoretical framework above, energy conservation became a prominent topic in Bogotá around 2016, when the Mayor's Office of Bogotá decreed The 113th Decree of March 16th, 2016, "Through which transitional measures and environmental guidelines are established to promote the conservation of electric energy in Bogotá, D.C." (Alcaldía Mayor de Bogotá, 2016). In the document, it is exposed that Bogotá is, indeed, in need of an energy conservation scheme due to an extensive amount of reasons and arguments, presented in the document (see Annex 2).

This means that a study such as this one may be necessary towards Bogotá's clean energy goal. Energy recovery and recycling is one of the primary and most basic energy recovery systems available, as it was stated previously, where energy recovery is believed to be the bridge towards renewables (Ayres & Ayres, 2010).

5.2. Vehicle Energy Recovery Systems In The TransMilenio

Having presented the FRBS and ERBS and the TransMilenio routes and Scania buses in the theoretical framework, the following section contains the theoretical implementation of the RBS as components of the buses. It is very important to mention that the different data produced in this section of the monograph may be inaccurate for investigation's sake: Some data was not found and/or couldn't be calculated, and so it has been replaced with estimated values. Each case is detailed below and in section 7.

5.2.1. Scania F340

The Scania F340 uses EBS and Brake-By-Wire systems, and has 4 axes. This means that a serial ERBS can be installed. On the other hand, an FRBS could be installed as well. One flywheel is to be theoretically installed per axis.

The bus weighs 19.500kg empty, while fully loaded with passengers, around 45.200 kg and reaches an average velocity of 23kph, or 6.38m/s. (El Espectador, 2019).

5.2.1.1. Flywheel RBS. In order to not waste more natural gas fuel, a total of 3kmh, or 0.83m/s was subtracted from the bus velocity to compensate for the FRBS's weight.

The GKN Gyrodrive KERS's flywheel and motor-only mass is 60kg. If one was to be installed in each axis, then the total mass would be:

$$45.200\text{kg} + (60\text{kg} \times 4) = 45.440\text{kg}$$

For clarification, the formula for kinetic energy is the following:

$$\frac{mv^2}{2} = F$$

Thus, the total kinetic energy obtained in the flywheels would be:

$$\frac{(45.440\text{kg})(5.5\text{m/s})^2}{2} = 687.280\text{J}$$

Which means that the total energy generation for a single top-velocity to zero brake is 687,28kJ, which is the amount of kinetic energy the F340 produces each time it brakes from 20kph to 0. The flywheel's maximum energy storage is around 1.200kJ, so it is enough to store the energy.

Since the efficiency of the generator (85%) is already known (see section 6.3.1), the total energy can be obtained:

$$(687{,}28kJ)(0{,}85) = 584{,}188kJ$$

So, the total recovered electrical energy of the flywheel using the motor-generator will be around 584,2kJ each time it brakes.

For the small route of B55EX, the bus would only brake at a station 3 times. As such, the total energy produced would be:

$$(584{,}188kJ)(3) = 1.752{,}564kJ$$

And for the long route of 8EA, the bus would brake at a station 33 times. The total energy produced would be:

$$(584{,}188kJ)(33) = 19.278{,}204kJ$$

The final results for the electrical energy produced by the FRBS of a F340 are **1.752,564kJ at minimum** and **19.278,204kJ at maximum** in one single route, which will be stored in the battery.

5.2.1.2. Electromagnetic RBS. For the ERBS, instead of having a discharge station at every stop, the entire charge will be stored in a battery instead. Since the resulting energy can be stored in a battery as small as a golf cart's, this battery will be used in the calculations. The battery efficiency is considered to be 100%. Of course, this means that experimentally, the battery efficiency may change, and yield a different result. As it was explained at the beginning of the section 8.2, this is due to investigative reasons.

This battery is assumed to be 10kWh (36.000kJ) in capacity, and 30kg in mass. (average mass of a large golf cart battery)

Because of the added battery mass, the vehicle's mass and velocity change, and its kinetic energy does too. The speed was reduced by 1kph, or 0.2m/s to maintain consistency.

$$45.200\text{kg} + 30kg = 45.230\text{kg}$$

The total kinetic energy obtained by the MG would be:

$$\frac{(45.230\text{kg})(6.1\text{m/s})^2}{2} = 841.504{,}15\text{J}$$

Now, the entire data is plugged into the work/energy equation for the total energy produced. The battery efficiency is 100%, and the motor-generator efficiency is 90%, as showcased in the theoretical framework.

$$(0.9)(1)(841{,}50415kJ) = 757{,}353735kJ$$

Now, this energy is just the energy generated from one brake action. As for the 3 and 33 brake actions that the B55EX and 8EA involve the energy produced is shown in the following equations. For B55EX:

$$(757{,}353735kJ)(3) = 2.272{,}061205kJ$$

And for the long route of 8EA:

$$(757{,}353735kJ)(33) = 24.992{,}67326kJ$$

Thus, the energy produced by the ERBS of a F340 is between **2.272,061205kJ at minimum** and **24.992,67326kJ at maximum**.

5.2.2. Scania K320

The Scania K320 also uses EBS and Brake-By-Wire systems like the biarticulated F340. As such, a serial ERBS and a FRBS can be installed.

The bus's total mass was not found, so the mass of a very similar Scania vehicle, the K340, was taken into account, purely for investigative reasons, as explained at the beginning of the section 8.2. The K340 is essentially the same as the K320, notably differing in that the K340 doesn't have an articulation axis. The total mass of the K340, and therefore the estimated mass of the K320 while empty is 15.600kg (Alternative Fuels, Energy and Environmental Protection Investigation Group, 2014).

Since the maximum passenger capacity of the K320 is 160, and the total mass of the biarticulated F340 is known without passengers, a simple rule of three can be made to find the passenger mass used for the F340:

$$\frac{45.200kg - 19.500kg}{250p} = 102.8kg$$

Where *p* is passengers. Therefore, to make the K320 constant with the F340, the maximum weight would be $102.8kg \ \times 160 = 16.448kg$ which, added to the empty K320 mass of 15.600kg, the total mass for the fully loaded bus is around $15.600kg + 16.448kg = 32.048kg$.

Additionally, since the bus is lighter, the velocity can be increased slightly in comparison to the F340. According to TransMilenio S.A. (2020), the average speed of a trunk bus is 25kph.

5.2.2.1. Flywheel RBS. The K320 can also have a FRBS installed, albeit using only 3 axes instead of the 4 the F340 can use. If one was installed for each axis, then the total mass would be:

$$32.048\text{kg} + (60\text{kg} \times 3) = 32.228\text{kg}$$

Additionally, instead of a 3kmh subtraction in speed, the K320 case will only be subtracted 2kph or 0.55m/s. Therefore, the total kinetic energy the flywheels obtain from a brake would be:

$$\frac{(32.228\text{kg})(6.38\text{m/s})^2}{2} = 655.910{,}7016\text{J}$$

As such, the total energy generated from a single brake is 655,9107016kJ. Converted to electrical energy using the efficiency of the generator, the total obtained electrical energy is:

$$(0.85)(655{,}9107016kJ) = 557{,}5240964kJ$$

As such, the obtained electrical energy per brake is 557,5240964kJ. The following are the calculations for both routes:

For the B55EX:

$$(557{,}5240964kJ)(3) = 1.672{,}572289kJ$$

For the 8EA:

$$(557{,}5240964kJ)(33) = 18.398{,}29518kJ$$

As such, the electrical energy values produced by the FRBS of a K320 are **1.672,572289kJ at minimum** and **18.398,29518kJ at maximum**.

5.2.2.2. Electromagnetic RBS. The exact same battery as the F340 is used. The speed was also reduced by 1kph, or 0.2m/s in the K320 to maintain consistency.

$$32.048\text{kg} + 30kg = 32.078\text{kg}$$

So, the total kinetic energy is as follows:

$$\frac{(32.078\text{kg})(6.6\text{m/s})^2}{2} = 698.658{,}84\text{J}$$

As with the F340, the battery and MG efficiency remain the same:

$$(0.9)(1)(698{,}65884\text{k}J) = 628{,}792956kJ$$

For the brake actions, the energy is multiplied again, as follows, for the B55EX:

$$(628{,}792956kJ)(3) = 1.886{,}378868kJ$$

And for the long route of 8EA:

$$(628{,}792956kJ)(33) = 20.750{,}16755kJ$$

The K320's ERBS will produce between **1.886,378868kJ at minimum** and **20.750,16755kJ at maximum** electrical energy.

5.3. Contrast Of The Aforementioned Systems

The following table (Table 3) shows the energy comparison between the systems.

Table 3

Comparison of produced energy from each scenario

	F340 + FRBS	F340 + ERBS	K320 + FRBS	K320 + ERBS
Route B55EX energy prod.	1.753kJ	2.272kJ	1.673kJ	1.886kJ
Route 8EA energy prod.	19.278kJ	24.993kJ	18.398kJ	20.750kJ

Note. Different energy results obtained in kJ, rounded to the nearest integer. Own work.

The results in Table 3 are immediately apparent as the ERBS beats the FRBS by a couple kilojoules in both cases. Thus, the highest generating system is the ERBS, and therefore is the only system which will be taken into account, eliminating the need to calculate the energy transfer rate from the bus to the station in the case of the flywheel.

5.4. Comparison To The City's Energy Expenditure

According to TransMilenio S.A. (2020), the B55EX route is 7.5km long, and the 8EA route is around 21.8km long. The B55EX route operates from 6:00 a.m. to 8:30 a.m. on weekdays only, and the 8EA from 4:30 a.m. to 11:00 p.m. on weekdays, 5:00 a.m. to 11:00p.m. on Saturdays, and 5:30 a.m. to 10:00 p.m. on Sundays and holidays. This means that the B55EX route has 2.5 hours to operate each day, while the 8EA gets either 18,5h, 18h, or 16,5 each day.

Colombia has 18 holidays. A non-leap year has 242 working days (Mon to Fri), minus the holidays, 49 Saturdays, and 68 Sundays and holidays.

If the 23kph velocity of the F340 is averaged with the 25kph velocity of the K320, a value of 24kph is usable to find the number of times the route is conducted in one day.

Taking into account that $t = \frac{d}{v}$ where *t* is time, *d* displacement and *v* velocity (expressed as speed *s* for this calculation), that every stop has an average time of 1 minute in which the bus is standing still (which is 0,016h), and that the bus could take up to 5 minutes between roundtrips while reassigning service (which is 0,083h), the following sections calculate for the time to complete one single trip of a route, and how much energy it would produce per day, per month, and per year, for both buses, producing the following equation:

$$t_{trip} = \left(\frac{d}{s}\right) + \left(0{,}016h \times n_{stops}\right) + 0{,}083h$$

Where t_{trip} is the time taken in one trip, and n_{stops} is the number of stops the route has.

5.4.1. B55 Express Route

Taking the aforementioned variables and equation directly above into account, the following describes the amount of time it would take to complete the route once.

$$0{,}4435h = \left(\frac{7{,}5km}{24km/h}\right) + (0{,}016h \times 3) + 0{,}083h$$

This means that the route could be completed $\frac{2{,}5h}{0{,}44h} = 5{,}63$ times in the service schedule (150min being the 2.5h the service is active). Since the schedule isn't necessarily rigid, it counts as 6 times. Therefore, the total energy recovered by a F340 in a single day for the B55EX is:

$$(2.272\text{kJ})(6) = 13.632\text{kJ}$$

And by a K320:

$$(1.886\text{kJ})(6) = 11.316\text{kJ}$$

If the route is completed daily, then it would work 5 days a week, for the entire month, for the entire year, with holidays excluded, therefore 242 days in one year. The total energy production for a F340 in one year of running the B55EX would be:

$$(13.632\text{kJ})(242) = 3.298.944\text{kJ}$$

And:

$$(11.316\text{kJ})(242) = 2.738.472\text{kJ}$$

For a K320.

5.4.2. 8th Easy Route

The equation for the 8EA is the following:

$$1{,}52h = \left(\frac{21{,}8km}{24km/h}\right) + (0{,}016h \times 33) + 0{,}083h$$

The route then could be completed $\frac{18{,}5h}{1{,}52h} = 12{,}2$ times in a weekday, $\frac{18h}{1{,}52h} = 11{,}8$ on a Saturday, and $\frac{16{,}5h}{1{,}52h} = 10{,}9$ times on a Sunday or holiday. For all days, the total trip counter is rounded up to the closest integer to maintain consistency, making it 13 times on the week, 12 times on Saturdays, and 11 times on a Sunday or holiday. As such, the following equations shows the energy recovered each day:

For a F340:

$$(24.993\text{kJ})(13) = 324.909\text{kJ}$$

$$(24.993\text{kJ})(12) = 299.916\text{kJ}$$

$$(24.993\text{kJ})(11) = 274.923\text{kJ}$$

And for a K320:

$$(20.750\text{kJ})(13) = 269.750\text{kJ}$$

$$(20.750\text{kJ})(12) = 249.000\text{kJ}$$

$$(20.750\text{kJ})(11) = 228.250\text{kJ}$$

Unlike the B55, if the route is completed every single day, the total energy production would vary depending on the number of days. As it was stated before, there are 242 weekdays, 49 Saturdays, and 68 Sundays and holidays. Consequently, the following equation describes the total energy recovered in one year:

For a F340:

$$(324.909kJ \times 242) + (299.916kJ \times 49) + (274.923kJ \times 68) = 112.018.626kJ$$

For a K320:

$$(269.750kJ \times 242) + (249.000kJ \times 49) + (228.250kJ \times 68) = 93.001.500kJ$$

5.4.3. Comparison

Following the values obtained in the previous section, the absolute minimum value would be a K320 running the B55EX for a year, which is 2.738.472kJ, and the absolute maximum which is a F340 running the 8EA for a year, which is 112.018.626kJ. The studies done by Martinez et al. (2013) are in GWh, so the values are converted as follows:

Smallest value – K320 on B55EX

$$\frac{2.738.472kJ}{3600} = 760.68kWh = 0.00076GWh$$

F340 on B55EX

$$\frac{3.298.944\text{kJ}}{3600} = 916.37kWh = 0.00091GWh$$

K320 on 8EA

$$\frac{93.001.500kJ}{3600} = 25833.75kWh = 0.026GWh$$

Greatest value – F340 on 8EA

$$\frac{112.018.626kJ}{3600} = 31116.28kWh = 0.031GWh$$

Now, as Table 2 calculates both Cundinamarca and Bogotá, it's important to only leave Bogotá as a variable. Therefore, the following equations solve for the amount of Bogotá-only energy.

$$(3.265GWh - 81GWh) + (9.194GWh - 535GWh) = 11.483GWh$$

Where the 81GWh and 535GWh are the Official and Street Lighting values, which are subtracted because the predicted aggregated value does not take them into account (Martínez, et al., 2013).

$$\frac{11.483GWh}{19.024GWh} = \frac{8.659GWh}{x}$$

Where *x* is:

$$\frac{(19.024GWh)(8.659GWh)}{11.483GWh} = 14.345{,}45GWh$$

Thus, Bogotá's consumption, without the Street Lighting and Official values would be predicted to be 14.345GWh in 2020.

From here on, the analysis will be a very speculative set of data, in order to get a conclusion of the data analyzed.

Needless to say, this value is extremely big compared to the 0.031GWh total energy produced by the F340 ERBS. However, the other routes still exist. Calculating all of the routes, however, is out of the spectrum of this investigation; so, the following rudimentary process will be calculated: Since, technically, the K320 on the B55EX is the least possible energy production in the entire TransMilenio system, and the F340 on the 8EA is the greatest possible, then an average between those two and also the other two calculated values should be able to represent the other 92 routes of the Trunk subsystem. Therefore:

$$\frac{0{,}00076GWh + 0{,}00091GWh + 0{,}026GWh + 0{,}031GWh}{4} = 0{,}015GWh$$

The percentage of days is not taken into account for simplicity's sake, so the following data could be very inaccurate, but still poses a decent grade of accuracy to make a conclusion:

$$(0{,}015GWh \times 92) + 0.00076GWh + 0.031GWh = 1{,}69GWh$$

Is what the whole system would produce at a time, fairly inaccurately.

Now, the following equations find the value of Street Lighting if it was projected on the predictions made by Martínez et al. (2013); since it is known that Street Lighting and Official were 3% and 4% of the total value respectively, it can be assumed that the total value without those two sectors is equivalent to 93% of the actual value. Another rule of three finds the 100%:

$$\frac{14.345{,}45GWh}{x} = \frac{0{,}93}{1}$$

Where *x* would be:

$$\frac{14.345{,}45GWh}{0{,}93} = 15.425{,}22GWh$$

Rounded to the nearest hundredth. This also means that, since this value is now complete, 3% of it is Street Lighting, which would be:

$$15.425{,}22GWh \times 0.03 = 462.76GWh$$

So, therefore, comparing both the biggest possible value produced by an ERBS running on, if possible, every single bus, every single day, for a year, and the lowest value in the energy prediction made by Martínez et al., the ratio is the following:

$$\frac{462.76GWh}{1{,}69GWh} = \frac{273{,}82}{1}$$

Where 273,82 TransMilenio systems would be required to power at least the street lighting sector of the city in 2020.

6. Conclusions

As a conclusion, the implementation of an energy recovery system like the RBS in the Bogotá TransMilenio is, while possible, not enough to power even the street lighting system in the entire city. However, the energy generated is still a rather big amount of energy. Thus, it may not work as a source of energy for the city itself, but it could be used for other projects such as the electric consumption of the bus itself, or only the public transport station infrastructure network. This is, however, an objective that is not covered by this investigation.

It is true that Bogotá is in need of self-sustaining energy like any other megacity. Being the capital city of Colombia, it is one of the most important cities in the entire continent and thus has a quite high energy expenditure. Supported by the general conception of renewable energy, this investigation, based on Ayres & Ayres (2010), supports the transformation of Bogotá's energy framework to one based on energy recovery and renewables, even if the project proposed by this investigation isn't enough for the city.

As for the tested recovery systems, it could be said that this investigation helped prove the efficiency of vehicle-type energy recovery systems, mainly through RBS. Perhaps, the RBS tested in this investigation would be enough to power smaller systems, like the buses themselves, or maybe the lighting of the stations only. The fact that one bus alone can, at worst, produce 760kWh, is a charge that, while small in comparison to the entire city, still is a decent amount of energy that could be called free, which can be used in practically anything apart from the city itself.

Additionally, the investigation aimed to compare the Flywheel and the Electromagnetic type RBSs. Due to omitted details, this comparison is not a very strong one, but it could conclude in a different note; the efficiency of the generator and the battery are very important factors when it comes to RBS. However, due to the simpler system of less energy consumption and not having to convert between many different types of energy, the Electromagnetic type RBS seems to be the most useful when it comes to slow-moving heavy vehicles like city buses, while the FRBS still remains one of the best choices for boost KERS like on F1.

Moreover, as it is summarized in sections 5.3 and 5.4.3, the resulting data from the calculations was effectively compared and contrasted. Using the found equations and data from various sources (cited), the found data was used to make conclusions and different analyses.

The conclusion of the whole investigation is, unfortunately, not a successful one; the energy produced by the best possible outcome of the proposed system isn't enough to power the least consuming sector of the city's energy expenditure. However, the public lighting system is extremely big in a megacity such as Bogotá, and even then, the energy recovery produced an energy output that should not be underestimated. If another objective outside of this investigation could benefit from the projected amount of recovered energy, this investigation's main objective still remains; to prove the importance of energy recovery in today's world, which desperately needs renewable energy, by implementing it on a system that is constantly moving.

7. Recommendations

Because of investigation constraints, a selection of data had to be assumed instead of calculated. Motor-Generator efficiency for the FRBS was assumed to be 85% as stated by Prof. Pullen in his work (The Status and Future of Flywheel Energy Storage, 2019). This data could be taken directly from a selected MG model.

Motor-Generator efficiency for the ERBS was assumed to be 90% (refer to section 3.2.2.) as stated by Micah Toll in their article (Regenerative braking: how it works and is it worth it in small EVs?, 2018). Additionally, battery efficiency was assumed to be 100%. As with the FRBS MG referred to above, this data could be taken directly from both the MG and the battery.

The total mass for the Scania K320 was assumed to be 32.048kg. This was inferred by comparing the K320 to a similar Scania bus, the K340, for which the corresponding data was found (refer to section 5.2.2.). This data could be taken by studying the K320 with and without passengers.

Because of test limitations, only the times a bus braked at a station were counted. To make the analysis more exact, other brake actions could be taken into account, such as streetlights, reductions of velocity because of traffic, and others.

Additionally, bus availability was very roughly estimated. The time taken for a bus to reassign service to the same or another route and the time taken at each station, the amount of Scania buses in the entire TransMilenio fleet (or, on the contrary, the compatibility of other buses such as Marcopolo/Superpolo, Mercedes Benz, or Volvo buses to equip EM RBS) could be taken exactly to improve the results of the analysis.

The exact 2020 electrical energy consumption details for Bogotá D.C. are unknown and had to be calculated using data from Martínez et al. in their work (Análisis de la situación energética de Bogotá y Cundinamarca, 2013). In order to get real data for section 5.4, a complete analysis could be conducted on the Bogotá energy sector.

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9. Appendix

9.1. Annex 1 – Análisis de la situación energética de Bogotá y Cundinamarca

Martínez, A., Afanador, E., Zapata, J. G., Núñez, J., Ramírez, R., Yepes, T., & Garzón, J. C. (2013, Julio). *Análisis de la situación energética de Bogotá y Cundinamarca*. Fundación para la Educación Superior y el Desarrollo. Pages 101-103 and section 3.2 (pages 139-147)

Anexos

Anexo 1 Fuentes de información del consumo de energía eléctrica para la Región Capital entre 2000 y 2012.

Tabla A. Consumo de energía eléctrica en la Región Capital entre 2000 y 2012 (Gwh)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
1. Región Capital	**8.454**	**8.423**	**8.775**	**9.036**	**9.470**	**9.888**	**10.419**	**11.088**	**11.539**	**11.561**	**11.900**	**12.310**	**12.459**
Residencial	3.457	3.477	3.528	3.581	3.687	3.799	3.915	4.049	4.241	4.315	4.369	4.435	4.461
Comercial	1.533	1.534	1.732	1.837	2.033	2.241	2.498	2.851	2.967	3.045	3.137	3.275	3.417
Industrial	2.681	2.626	2.803	2.938	3.082	3.212	3.409	3.593	3.702	3.571	3.762	3.986	3.966
Oficial	484	480	411	412	400	371	358	351	381	377	377	355	353
Alumbrado Público	299	306	300	269	268	265	238	243	248	254	256	259	262
1.1 Bogotá	**6.575**	**6.519**	**6.751**	**6.918**	**7.311**	**7.634**	**7.983**	**8.455**	**8.719**	**8.743**	**8.901**	**9.081**	**9.194**
Residencial	2.993	3.010	3.054	3.099	3.163	3.255	3.334	3.426	3.572	3.609	3.650	3.692	3.699
Comercial	1.303	1.303	1.472	1.561	1.727	1.904	2.123	2.399	2.498	2.603	2.687	2.798	2.911
Industrial	1.602	1.527	1.610	1.669	1.843	1.925	2.011	2.117	2.106	1.981	2.011	2.055	2.050
Oficial	426	422	362	363	352	326	315	309	335	339	340	320	317
Alumbrado Público	251	257	252	226	225	223	200	204	208	212	213	216	218
1.2 Cundinamarca	**1.879**	**1.904**	**2.025**	**2.118**	**2.159**	**2.254**	**2.436**	**2.633**	**2.819**	**2.818**	**3.000**	**3.228**	**3.265**
Residencial	464	467	474	481	524	544	581	623	669	706	719	742	762
Comercial	231	231	260	276	306	337	376	452	469	443	450	477	506
Industrial	1.079	1.100	1.193	1.269	1.239	1.286	1.398	1.476	1.596	1.590	1.751	1.931	1.916
Oficial	58	58	49	49	48	44	43	42	46	38	37	35	36
Alumbrado Público	48	49	48	43	43	42	38	39	40	42	43	43	45
1.2.1 Subsabana	**1.729**	**1.751**	**1.863**	**1.949**	**1.986**	**2.074**	**2.241**	**2.422**	**2.594**	**2.593**	**2.760**	**2.970**	**3.004**
Residencial	427	429	436	443	482	500	535	573	616	649	661	683	701
Comercial	212	212	240	254	281	310	346	416	431	407	414	438	466
Industrial	992	1.012	1.097	1.167	1.139	1.184	1.287	1.358	1.469	1.463	1.611	1.776	1.763
Oficial	53	53	45	46	44	41	40	39	42	35	34	32	33
Alumbrado Público	44	45	44	40	39	39	35	36	36	39	39	40	41

Fuente: Elaborado a partir de información de Codensa S.A. ESP, SUI y DANE

Tabla B. Consumo de energía eléctrica per cápita en la Región Capital entre 2000 y 2012 (Kwh por habitante)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
1. Región Capital	**1.009**	**987**	**1.011**	**1.024**	**1.055**	**1.084**	**1.125**	**1.179**	**1.208**	**1.192**	**1.209**	**1.233**	**1.230**
Residencial	413	408	406	406	411	417	423	430	444	445	444	444	440
Comercial	183	180	200	208	227	246	270	303	311	314	319	328	337
Industrial	320	308	323	333	343	352	368	382	388	368	382	399	392
Oficial	58	56	47	47	45	41	39	37	40	39	38	36	35
Alumbrado Público	36	36	35	30	30	29	26	26	26	26	26	26	26
1.1 Bogotá	**1.043**	**1.017**	**1.035**	**1.044**	**1.086**	**1.116**	**1.149**	**1.199**	**1.219**	**1.204**	**1.209**	**1.216**	**1.214**
Residencial	475	469	468	468	470	476	480	486	499	497	496	494	489
Comercial	207	203	226	236	256	278	306	340	349	359	365	375	384
Industrial	254	238	247	252	274	281	290	300	294	273	273	275	271
Oficial	68	66	56	55	52	48	45	44	47	47	46	43	42
Alumbrado Público	40	40	39	34	33	33	29	29	29	29	29	29	29
1.2 Cundinamarca	**905**	**899**	**937**	**963**	**964**	**989**	**1.051**	**1.116**	**1.176**	**1.156**	**1.211**	**1.282**	**1.277**
Residencial	223	220	219	219	234	239	251	264	279	290	290	295	298
Comercial	111	109	121	126	136	148	162	192	195	182	182	189	198
Industrial	519	519	552	577	553	564	603	626	666	652	707	767	749
Oficial	28	27	23	22	21	19	19	18	19	15	15	14	14
Alumbrado Público	23	23	22	20	19	19	16	17	17	17	17	17	17
1.2.1 Subsabana	**1.402**	**1.377**	**1.422**	**1.447**	**1.437**	**1.463**	**1.544**	**1.632**	**1.710**	**1.672**	**1.743**	**1.836**	**1.820**
Residencial	346	338	333	329	349	353	368	386	406	419	418	422	425
Comercial	172	167	183	189	203	219	238	280	284	263	261	271	282
Industrial	805	795	838	867	824	835	887	915	968	943	1.017	1.098	1.068
Oficial	43	42	35	34	32	29	27	26	28	22	22	20	20
Alumbrado Público	36	35	34	29	29	28	24	24	24	25	25	25	25

Fuente: Elaborado a partir de información de Codensa S.A. ESP, SUI y DANE

Tabla C. Participación por sector y por Zonas del Consumo de Energía eléctrica en la Región Capital entre 2000 y 2012

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
1. Región Capital	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Residencial	41%	41%	40%	40%	39%	38%	38%	37%	37%	37%	37%	36%	36%
Comercial	18%	18%	20%	20%	21%	23%	24%	26%	26%	26%	26%	27%	27%
Industrial	32%	31%	32%	33%	33%	32%	33%	32%	32%	31%	32%	32%	32%
Oficial	6%	6%	5%	5%	4%	4%	3%	3%	3%	3%	3%	3%	3%
Alumbrado Público	4%	4%	3%	3%	3%	3%	2%	2%	2%	2%	2%	2%	2%
1.1 Bogotá	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Residencial	46%	46%	45%	45%	43%	43%	42%	41%	41%	41%	41%	41%	40%
Comercial	20%	20%	22%	23%	24%	25%	27%	28%	29%	30%	30%	31%	32%
Industrial	24%	23%	24%	24%	25%	25%	25%	25%	24%	23%	23%	23%	22%
Oficial	6%	6%	5%	5%	5%	4%	4%	4%	4%	4%	4%	4%	3%
Alumbrado Público	4%	4%	4%	3%	3%	3%	3%	2%	2%	2%	2%	2%	2%
1.2 Cundinamarca	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Residencial	25%	25%	23%	23%	24%	24%	24%	24%	24%	25%	24%	23%	23%
Comercial	12%	12%	13%	13%	14%	15%	15%	17%	17%	16%	15%	15%	16%
Industrial	57%	58%	59%	60%	57%	57%	57%	56%	57%	56%	58%	60%	59%
Oficial	3%	3%	2%	2%	2%	2%	2%	2%	2%	1%	1%	1%	1%
Alumbrado Público	3%	3%	2%	2%	2%	2%	2%	1%	1%	1%	1%	1%	1%
1.2.1 Subsabana	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Residencial	25%	25%	23%	23%	24%	24%	24%	24%	24%	25%	24%	23%	23%
Comercial	12%	12%	13%	13%	14%	15%	15%	17%	17%	16%	15%	15%	16%
Industrial	57%	58%	59%	60%	57%	57%	57%	56%	57%	56%	58%	60%	59%
Oficial	3%	3%	2%	2%	2%	2%	2%	2%	2%	1%	1%	1%	1%
Alumbrado Público	3%	3%	2%	2%	2%	2%	2%	1%	1%	1%	1%	1%	1%

Fuente: Elaborado a partir de información de Codensa S.A. ESP, SUI y DANE

El pronóstico de potencia máxima del área de Codensa se obtiene con base en el pronóstico de demanda de energía y el factor de carga anual histórico -similar a cómo lo hace la UPME.

Análisis de demanda por zonas

Codensa realiza análisis de cinco zonas: Sabana Norte, Sabana Sur, Urbano Norte, Urbano Centro y Urbano Sur. Con base en el análisis del crecimiento de demanda de potencia máxima en las diferentes zonas y subestaciones, elabora las proyecciones y el plan de inversiones en infraestructura.

Para las proyecciones de demanda toma en cuenta el crecimiento histórico del número de usuarios, de la demanda de energía y la identificación de proyectos importantes -que pueden ser de tipo industrial, vivienda o infraestructura vial -que solicitan conexión a la red.

La identificación de dichos proyectos y su impacto en la configuración del sistema eléctrico se hace por sondeo. No existe una metodología definida para la interacción entre el proceso de ordenamiento territorial y el del servicio de energía. En general, la expansión de las redes va detrás de la demanda y resulta, en cierta forma, acorde a los incentivos regulatorios de remuneración a la distribución mediante el costo medio histórico- el cual no mira las prospectivas de crecimiento de la demanda.[80] Tampoco consulta las orientaciones de la planeación territorial tal y como se analizó en el capítulo 2.

En lo que respecta al STR, los proyectos son presentados a la UPME y ésta los evalúa tomando en cuenta modelos de planeamiento que consideran el STN y las proyecciones de la demanda nacional.

En última instancia, a partir de las series históricas de demanda por subestaciones, el factor de diversidad y de coincidencia, Codensa emplea un modelo de optimización con el que busca consistencia entre la proyección individual, zonal y global.

3.2 Proyecciones de demanda de energía eléctrica en el corto plazo

Con el propósito de proyectar la demanda de energía eléctrica de la región de Bogotá y Cundinamarca hasta 2014, se ajusta un modelo de series

[80] De acuerdo con las señales regulatorias de la CREG, el operador de red, OR realiza la expansión en la me-dida que el costo medio de la misma no supere el costo medio del cargo de distribución aprobado. Así, por ejemplo, la configuración de la red de tensión media no necesariamente favorece la localización y conexión de la industria en determinados sitios donde los cargos de distribución sean menores y así poder obtener menores costos de producción.

de tiempo univariadas a las ventas mensuales de electricidad[81] en el área Codensa -que incluye las ventas de Codensa y de otros comercializadores -entre enero de 2005 y febrero de 2013.

Se ajusta un modelo ARIMA siguiendo la metodología de Box y Jenkins (1970). Las pruebas estadísticas, no presentadas acá, no rechazaron la existencia de una raíz unitaria simple y de una raíz unitaria estacional, de manera que se incluyeron términos estacionales al modelo. El modelo especificado, con base al criterio de información de Schwarz (BIC), es un $SARIMA(2,1,0)(2,1,1)$. La estimación es:

$$\Delta\Delta_{12}v_t = -1.04\Delta v_{t-1} - 0.45\Delta v_{t-2} - 0.02\Delta_{12}v_{t-1} - 0.21\Delta_{12}v_{t-2} - 0.80e_{t-12}$$

En donde v_t denota las ventas mensuales de energía eléctrica medidas en GWh mes, Δ es el operador diferencia, y e_t es un error gaussiano.

Resultados de las proyecciones

Las proyecciones, junto con los intervalos de predicción, se presentan en la Tabla 21 y en el Gráfico 47. Se estiman pronósticos desde marzo de 2013 hasta diciembre de 2014, para un total de 22 meses adelante.

Tabla 21. Pronóstico de Ventas Corto Plazo (GWh/mes)

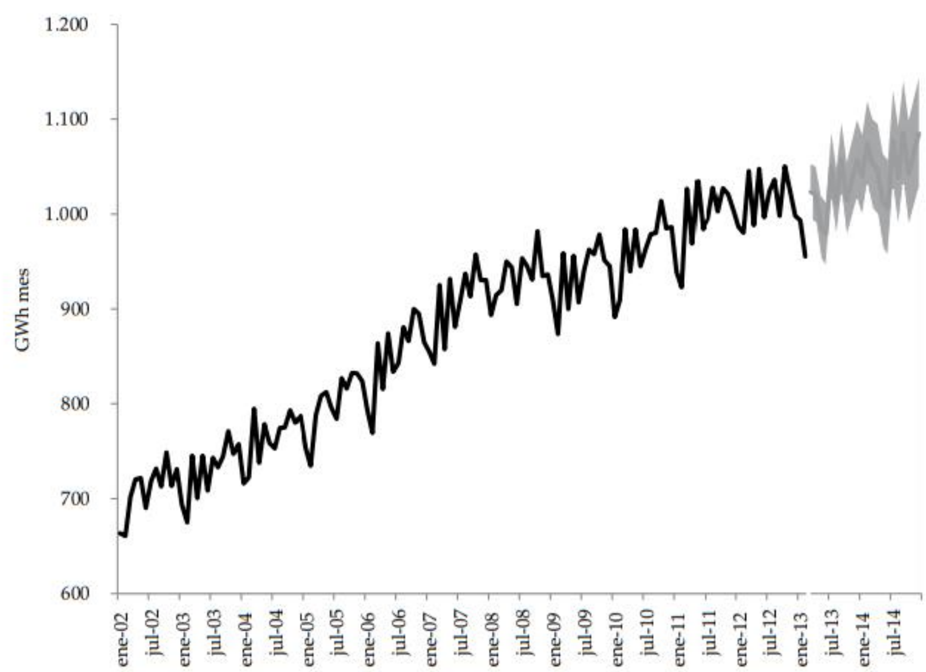
	Pronóstico	Umbral inferior (95%)	Umbral superior (95%)
mar-13	1.044	1.016	1.072
abr-13	1.003	975	1.031
may-13	1.045	1.013	1.077
jun-13	1.008	974	1.043
jul-13	1.024	989	1.060
ago-13	1.049	1.011	1.088
sep-13	1.033	993	1.072
oct-13	1.067	1.025	1.108

[81] Variables climáticas, como la temperatura o pluviosidad, son comúnmente usadas para modelar la demanda de energía en el corto plazo. En el caso de la región de Bogotá y Cundinamarca, los fenómenos climáticos no tienen un impacto relevante sobre la demanda de energía, así que se puede prescindir de información climática para las proyecciones de demanda de energía eléctrica. En otras regiones del país, como en la Costa Caribe, El Niño sí puede ser un fenómeno influyente en la demanda de energía eléctrica.

nov-13	1.047	1.004	1.090
dic-13	1.035	991	1.079
ene-14	1.008	962	1.054
feb-14	995	949	1.042
mar-14	1.068	1.019	1.117
abr-14	1.032	982	1.082
may-14	1.076	1.024	1.128
jun-14	1.035	981	1.088
jul-14	1.055	1.000	1.110
ago-14	1.078	1.022	1.134
sep-14	1.062	1.004	1.119
oct-14	1.096	1.037	1.155
nov-14	1.076	1.015	1.136
dic-14	1.064	1.002	1.125

Fuente: Cálculos propios

Gráfico 47. Proyección de Ventas de Energía Eléctrica Corto Plazo Área de Codensa OR- Marzo 2013 - Diciembre 2014



Fuente: Cálculos propios

De los pronósticos a diciembre de 2013, las ventas para el área de Codensa alcanzarán su pico en octubre (entre 1.025 y 1.108 GWh, según los intervalos de confianza) y su valle en abril (entre 975 y 1.031 GWh). Se estima que el mayor incremento en las ventas con respecto al mes del año anterior sería en septiembre, mientras que el menor crecimiento se experimentaría en mayo.

El pico de las ventas para 2014 sería visto en octubre (1037-1155 GWh), y el valle en febrero (949-1042GWh). Después de marzo de 2014, se estima que las ventas crecerán por encima del 2,75% con respecto al mismo mes del año anterior.

En cuanto a las ventas acumuladas en el año, se estima que en 2013 estarán entre 11.940 y 12.668 GWh, y para 2014 entre 11.997-13.292 GWh.

3.3 Proyecciones de demanda de energía eléctrica en el largo plazo

En esta sección se proyecta la demanda anual de energía en Bogotá y Cundinamarca (ByC) siete años adelante, hasta 2020. Aunque es deseable para el estudio elaborar proyecciones separadas para el Distrito Capital, para el área de Codensa y para el área de la Empresa de Energía de Cundinamarca, las restricciones en la información histórica y en los niveles de desagregación de las variables limitan aquel alcance (ver Anexo del capítulo 3).

Las proyecciones se estiman a partir de modelos de series de tiempo VAR y VEC, ajustados al consumo anual de energía eléctrica en función de variables típicamente usadas en la literatura, como el producto interno bruto per cápita y el precio de la energía eléctrica.[82]

[82] El precio de los sustitutos energéticos (fundamentalmente el gas natural) y la eficiencia energética son variables que frecuentemente se consideran en los modelos de proyección de demanda de energía.
El servicio de gas natural llegó a Bogotá en 1997, y entre ese año y 2002 ocurrió la principal expansión de cobertura del gas residencial; la cobertura actual es del 87%, y la porción restante corresponde a zonas de riesgo por inestabilidad geológica o por normalización de predios. Además, el consumo promedio de electri-cidad por suscriptor, como ya se señaló, se ha mantenido estable a pesar de la alta penetración del gas en la última década. Por esos motivos, no se considera que en el futuro cercano exista una sustitución de gas natural por electricidad que sea significativa. En el capítulo 4 se analiza de manera particular la competitivi-dad del gas natural frente a los combustibles líquidos para evaluar la incidencia en la demanda de gas natural vehicular y la competitividad del gas natural frente a otros combustibles en el consumo de gas natural en la industria, así como del gas natural frente a GLP y electricidad en el consumo residencial.
El desarrollo tecnológico, especialmente a través de los incrementos en la eficiencia de los electrodomésti-cos, es una variable que afecta el consumo de energía eléctrica residencial. Sin embargo, una verificación del impacto de dicha variable en la región Capital está fuera del alcance de este estudio, y requeriría de un nue-vo estudio como el realizado por la UN (2006) para la UPME.

Se estiman dos tipos de modelos. El primero es el "modelo agregado", en el que se pronostica el consumo total de energía en Bogotá y Cundinamarca. El segundo es el "modelo sectorial", en el que el consumo total de energía en la región se pronostica a partir del consumo de energía eléctrica desagregado según sectores de uso final: sector productivo (industrial y comercial) y sector residencial. La lógica de esta separación está en que la demanda de energía de cada sector responde a factores e incentivos distintos.

A continuación se enuncian las variables utilizar en los modelos y se describen la construcción y fuentes de los datos. Luego, se detallan los modelos econométricos estimados. Por último, se presentan los resultados de las proyecciones y se contrastan contra las proyecciones de la UPME y Codensa.

Variables y descripción de los datos

- *Consumo de energía eléctrica*

Se utiliza la serie de consumo anual de electricidad (en GWh) del área Codensa entre 1985 y 2012, proporcionada por la misma empresa. El área Codensa abarca a Bogotá, los municipios de la Sabana y cerca de 80 municipios de Cundinamarca. El consumo atendido en el área Codensa es la suma del consumo de los clientes regulados y clientes no regulados de la gran industria y comercio-cuyo consumo incluye el atendido por otros comercializadores a través de los peajes de Codensa. El consumo se puede desagregar según los sectores residencial, industrial, comercial, oficial y alumbrado público.

Geográficamente el área Codensa no abarca todos los municipios de Cundinamarca, así que para completar la serie agregada de consumo de Bogotá y Cundinamarca (ByC) se añadió a la serie de consumo del área Codensa la porción del consumo de Cundinamarca que es atendida por la EEC. El consumo atendido por EEC representa alrededor del 6% del atendido por Codensa, proporción que se ha mantenido estable según la información suministrada por XM (Tabla 22). Por lo tanto, suponiendo dicha participación estable:

$$Consumo\ de\ Bogotá\ y\ C/marca = Consumo\ del\ área\ Codensa * 1{,}06$$

Tabla 22. Participación de la Demanda de Energía de EEC OR y Codensa OR 2000 – 2012 (en porcentajes)

EMPRESA	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
CODENSA OR	22,7	22,2	22,1	21,5	21,5	21,6	22,0	22,7	23,1	22,5	22,7	22,8	22,4
EEC OR	1,4	1,4	1,4	1,3	1,3	1,3	1,3	1,3	1,3	1,4	1,3	1,3	1,4
EEC / Codensa	6,1	6,3	6,3	6,2	6,0	5,9	5,8	5,8	5,8	6,1	5,9	5,9	6,2

Fuente: XM

Ahora bien, el consumo de energía eléctrica no es igual a la demanda de energía eléctrica. Para suplir la demanda, los procesos de distribución y comercialización a través de las redes implican pérdidas de energía eléctrica que no llegan al consumidor final. Para obtener la demanda, al consumo se le deben agregar las pérdidas del sistema, de manera que:

$$Demanda\ de\ electricidad = Consumo\ de\ electricidad + pérdidas\ del\ sistema$$

Se supusieron unas pérdidas de 8% del consumo, con base en información de Codensa. Para obtener los pronósticos de demanda de energía eléctrica, el procedimiento que se sigue es ajustar los modelos al consumo de energía eléctrica, y una vez estimados los pronósticos, se agregan las pérdidas del sistema.

- *Tarifas*

La variable de precios de la energía eléctrica utilizada corresponde a las tarifas facturadas a los clientes de la región del área Codensa. El valor de las tarifas es el valor promedio anual en pesos por kWh facturado. En los sectores industrial y comercial, el valor de la tarifa corresponde al promedio ponderado entre las tarifas de los clientes regulados y las tarifas de los grandes clientes no regulados (que XM publica en forma agregada, anónima). Las tarifas están deflactadas con el índice de precios al productor (IPP) de 2005, y comprende observaciones entre 1985-2012 y proyecciones para 2013-2020 (elaboradas por Codensa).

No se cuenta con la serie histórica confiable de las tarifas cobradas por la EEC, pero dado que el consumo del área Codensa representa alrededor del 94% de la región de ByC, se considera que tomar únicamente las tarifas de Codensa es representativo y no afecta los resultados.

- *PIB*

El PIB real de Bogotá y Cundinamarca entre 1985-2011 proviene de las cuentas departamentales del DANE. La serie fue empalmada con la base 2005. El dato regional de 2012, el cual a la fecha no ha sido publicado por el DANE, se obtuvo de los pronósticos de tasa de crecimiento de los PIB departamentales elaborado por Fedesarrollo. Para Bogotá, el pronóstico de crecimiento es 4,0% y para Cundinamarca es 4,4%.

- *Población*

La población de Bogotá y Cundinamarca desde 1980 hasta 2012 corresponde a las estimaciones publicadas por el DANE a partir de los censos nacionales de 1995, 2000, y 2005.

- *Clientes residenciales*

Corresponde al número de clientes residenciales registrados por Codensa.

- *Dummy de racionamiento*

Se incluye una variable *dummy* o binaria para modelar el racionamiento energético que vivió el país en 1992, el cual fue un evento inusual que disminuyó temporalmente el consumo de electricidad. La variable es igual a 1 para el año 1992, e igual a 0 en cualquier otro caso.

- *Crisis económica*

Se incluye también una variable *dummy* para modelar la crisis económica que vivió el país en 1999 y que es un evento atípico para la serie del PIB. La variable es igual a 1 para el año 1999, e igual a 0 en cualquier otro caso.

Modelo de consumo de energía agregado

En el modelo agregado, el consumo total de energía eléctrica en la región es explicado a partir del PIB de la región y de las tarifas de la energía eléctrica.

El consumo total de energía (E) de este modelo corresponde a la suma del consumo de los sectores residencial, industrial y comercial. Se excluyen el sector oficial y el sector de alumbrado público puesto que su consumo y tarifa están determinados por negociaciones y regulaciones de los gobiernos locales. El PIB (Y) es la suma del PIB de Bogotá y de Cundinamarca. La tarifa (T) en este modelo se obtiene de las tarifas cobradas a los sectores residencial, industrial y comercial, ponderadas de acuerdo al consumo de cada sector. La tarifa, como ya se explicó, se considera una variable exógena del modelo[83]. Finalmente, se incluyeron dos variables

[83] Para realizar las proyecciones del consumo eléctrico, se incorporan exógenamente las proyecciones de la tarifa total ponderada, basada en las proyecciones de tarifas entre 2013 y 2020 elaboradas por Codensa.

dummy: una para el racionamiento eléctrico de 1992 (rac) y otra para la crisis económica de 1999 (cri).

Al aplicar la prueba de la traza de Johansen (ver Enderes, 2002) al consumo y el PIB, a las variables endógenas del modelo, no se rechaza la existencia de una relación de cointegración. Se procede a estimar un vector de corrección de errores (VEC) con una relación de cointegración. A partir de los criterios de información AIC y BIC, y verificando los supuestos del modelo, se especifica el orden del modelo con un rezago de las variables endógenas en nivel y un rezago de las variables endógenas diferenciadas.

El $VEC(1)$ estimado es:

$$\begin{bmatrix}\Delta E_t\\ \Delta Y_t\end{bmatrix}=\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix}\begin{bmatrix}1 & \beta\end{bmatrix}\begin{bmatrix}E_{t-1}\\ Y_{t-1}\end{bmatrix}+\begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}\begin{bmatrix}\Delta E_{t-1}\\ \Delta Y_{t-1}\end{bmatrix}+\begin{bmatrix}\gamma_1\\ \gamma_2\end{bmatrix}\begin{bmatrix}\Delta T_t\end{bmatrix}+\begin{bmatrix}\delta_{11} & \delta_{12}\\ \delta_{21} & \delta_{22}\end{bmatrix}\begin{bmatrix}rac_t\\ cri_t\end{bmatrix}+\begin{bmatrix}u_{1t}\\ u_{2t}\end{bmatrix}$$

Donde los u_{it} son errores que se suponen ruido blanco. Los resultados de las estimaciones de este y los demás modelos se presentan en el Anexo.

Modelo de consumo de energía sectorial

En este modelo, el consumo de energía de la región se desagrega según sectores de uso final de la electricidad. Se ajusta un "submodelo" a los sectores residencial, industrial y comercial, en el que el consumo de energía eléctrica de cada sector se explica a partir de diferentes variables que lo afectan de forma particular. De estos submodelos se estiman los pronósticos del consumo de energía eléctrica por sector, y se suman para obtener el pronóstico del consumo total.

En el primer submodelo, el consumo eléctrico del sector residencial (E^r) se explica a partir de los clientes residenciales (C) y la tarifa residencial (T^r). El modelo a estimar es:

$$\begin{bmatrix}\Delta E_t^{\,r}\\ \Delta C_t\end{bmatrix}=\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix}\begin{bmatrix}1 & \beta\end{bmatrix}\begin{bmatrix}E_{t-1}^{\,r}\\ C_{t-1}\end{bmatrix}+\begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}\begin{bmatrix}\Delta E_{t-1}^{\,r}\\ \Delta C_{t-1}\end{bmatrix}+\begin{bmatrix}\gamma_1\\ \gamma_2\end{bmatrix}\begin{bmatrix}\Delta T_t^{\,r}\end{bmatrix}+\begin{bmatrix}\delta_{11} & \delta_{12}\\ \delta_{21} & \delta_{22}\end{bmatrix}\begin{bmatrix}rac_t\\ cri_t\end{bmatrix}+\begin{bmatrix}u_{1t}\\ u_{2t}\end{bmatrix}$$

En donde el superíndice r denota al sector residencial, y los u_{it} son errores que se suponen ruido blanco.

El segundo submodelo contiene los sectores industrial y comercial en un sector denominado "productivo". El consumo eléctrico del sector productivo (E^{ic}), que es la suma de los consumos industrial y comercial, es explicado por el PIB (Y) y una tarifa ponderada según el consumo de ambos sectores (T^{ic}). El modelo a estimar es:

$$\begin{bmatrix}\Delta E_t^{\ ic} \\ \Delta C_t\end{bmatrix} = \begin{bmatrix}\alpha_1 \\ \alpha_2\end{bmatrix}\begin{bmatrix}1 & \beta\end{bmatrix}\begin{bmatrix}E_{t-1}^{\ ic} \\ C_{t-1}\end{bmatrix} + \begin{bmatrix}a_{11} & a_{12} \\ a_{21} & a_{22}\end{bmatrix}\begin{bmatrix}\Delta E_{t-1}^{\ ic} \\ \Delta C_{t-1}\end{bmatrix} + \begin{bmatrix}\gamma_1 \\ \gamma_2\end{bmatrix}\begin{bmatrix}\Delta T_t^{\ ic}\end{bmatrix} + \begin{bmatrix}\delta_{11} & \delta_{12} \\ \delta_{21} & \delta_{22}\end{bmatrix}\begin{bmatrix}rac_t \\ cri_t\end{bmatrix} + \begin{bmatrix}u_{1t} \\ u_{2t}\end{bmatrix}$$

En donde el superíndice ic denota la suma de los sectores industrial y comercial, y los u_{it} son errores que se suponen ruido blanco.

Resultados de las proyecciones

A los pronósticos del consumo de Bogotá y Cundinamarca, estimados de los modelos agregado y sectorial, se les ajustan las pérdidas del sistema para obtener el pronóstico de la demanda. Las pérdidas actuales se consideran alrededor del 8% del consumo, así que:

$$Pronóstico\ de\ Demanda\ de\ ByC = Pronóstico\ de\ Consumo\ de\ ByC * 1{,}08$$

Estos pronósticos ajustados de demanda de energía se presentan en la Tabla 23, y permiten ser comparados con los pronósticos de la UPME para la UCP Centro -que equivale a la región de Bogotá y Cundinamarca.

Tabla 23. Resultado de las Proyecciones de Energía para la Región - Escenario Base

Año	Modelo agregado		Modelo sectorial		Upme	
	GWh	Crec. %	GWh	Crec. %	GWh	Crec. %
2013	14.508	4,1	14.363	3,0	14.720	5,6%
2014	15.083	4,0	14.895	3,7	15.207	3,3%
2015	15.685	4,0	15.453	3,7	15.739	3,5%
2016	16.297	3,9	16.031	3,7	16.801	6,7%
2017	16.959	4,1	16.645	3,8	17.547	4,4%
2018	17.618	3,9	17.267	3,7	18.316	4,4%
2019	18.275	3,7	17.896	3,6	19.075	4,1%
2020	19.024	4,1	18.583	3,8	19.674	3,1%

Fuente: Cálculos propios

9.2. Annex 2 – Decreto No. 113 del 16 de Marzo de 2016

Alcaldía Mayor de Bogotá. (2016, March 16). *Decreto No. 113 del 16 de Marzo de 2016*. 10-14. Alcaldía Mayor de Bogotá.

ALCALDÍA MAYOR
DE BOGOTÁ, D.C.

DECRETO No. 113 DE

(16 MAR 2016)

"Por medio del cual se establecen medidas transitorias y lineamientos ambientales para promover el ahorro de energía eléctrica en la ciudad de Bogotá, D.C."

EL ALCALDE MAYOR DE BOGOTÁ, D. C.

En uso de sus facultades legales, en especial las conferidas por el numerales 1), 3) y 5) del artículo 38 del Decreto Ley 1421 de 1993, en concordancia con la Ley 1450 de 2011 (Plan Nacional de Desarrollo)

CONSIDERANDO:

Que la Constitución Política de 1991 en su artículo 80, establece que el Estado planificará el manejo y aprovechamiento de los recursos naturales, para garantizar su desarrollo sostenible, su conservación, restauración o sustitución. En el mismo sentido el artículo 334 prevé que la dirección general de la economía estará a cargo del Estado y este intervendrá por mandato de la Ley en la explotación de los recursos naturales.

Que el Principio de Precaución en materia ambiental tienen relación implícita con el Principio de Desarrollo Sostenible y el deber de protección del medio ambiente, por lo tanto dicho principio es acogido en nuestro ordenamiento jurídico en la Constitución política de 1991 en los artículos 8, 79, 80, 289 y 334. Dicho principio se predica que en caso de duda científica, sobre la posibilidad de determinar que una actividad puede causar daño grave o irreversible al medio ambiente, debe procederse a suspender aplazar, limitar o impedir la ejecución de la respectiva actividad hasta adquirir la seguridad científica.

Que los artículos 66 de la Ley 143 de 1994, por la cual se establece el régimen para la generación, interconexión, transmisión, distribución y comercialización de electricidad en el territorio nacional en concordancia con el 2° de la Ley 697 de 2001 tienen por objetivo estatal el ahorro de energía, así como su conservación y uso eficiente en el desarrollo de las actividades del sector eléctrico, para lo cual crearon la estructura legal, técnica, económica y financiera necesaria para lograr el desarrollo de este tipo de proyectos a corto, mediano y largo plazo, económica y ambientalmente viables, asegurando el desarrollo sostenible, al tiempo que generen la conciencia URE.

Que la Ley 99 de 1993, en su artículo 5°, numerales 32 y 33, asigna al Ministerio del Medio Ambiente, hoy Ministerio de Ambiente y Desarrollo Sostenible, la función de promover la formulación de planes de reconversión industrial ligados a la implantación de tecnologías ambientalmente sanas, así como también, promover en coordinación con las entidades competentes y afines, la realización de programas de sustitución de los recursos naturales no renovables, para el desarrollo de tecnologías de generación de energías no contaminantes ni degradantes.

Que en el artículo 66 de la Ley 99 de 1993, modificado por el artículo 214 de la Ley 1450 de 2011 -Por la cual se expide el Plan Nacional de Desarrollo, 2010-2014- los Grandes Centros Urbanos, dentro de los cuales se encuentra el Distrito Capital, ejercen dentro del perímetro urbano las mismas funciones atribuidas a las Corporaciones Autónomas Regionales y de Desarrollo Sostenible en lo que respecta a la protección y conservación del medio ambiente, con excepción de la elaboración de los planes de ordenación y manejo de cuencas hidrográficas.

Que en el artículo 31 de ley ambiental, se prevén como funciones de las Corporaciones Autónomas Regionales aplicables a los grandes centros urbanos, las de ejercer la función de máxima autoridad ambiental en el área de su jurisdicción; Fijar en el área de su jurisdicción, los límites permisibles de emisión, descarga, transporte o depósito de sustancias, productos, compuestos o cualquier otra materia que puedan afectar el medio ambiente o los recursos naturales renovables y prohibir, restringir o regular la fabricación, distribución, uso, disposición o vertimiento de sustancias causantes de degradación ambiental; Ejercer las funciones de evaluación, control y seguimiento ambiental de los usos del agua, el suelo, el aire y los demás recursos naturales renovables.

Que el Congreso de Colombia, por medio de la Ley 164 de 1994, aprobó la "*Convención Marco de las Naciones Unidas sobre el Cambio Climático*" realizada en Nueva York el 9 de mayo de

Por medio del cual se establecen medidas transitorias y lineamientos ambientales para promover el ahorro de energía eléctrica en la ciudad de Bogotá, D.C."

1992, en cuyos compromisos se encuentra: "art. 4 c) Promover y apoyar con su cooperación el desarrollo, la aplicación y la difusión, incluida la transferencia, de tecnologías, prácticas y procesos que controlen, reduzcan o prevengan las emisiones antropógenas de gases de efecto invernadero no controlados por el Protocolo de Montreal en todos los sectores pertinentes, entre ellos la energía, el transporte, la industria, la agricultura, la silvicultura y la gestión de desechos.

Que el numeral 3 del artículo 3 ibídem, se establece el principio de precaución con el fin de que las medidas a tomar dependiendo de la situación llegue a prever, prevenir o reducir al mínimo las causas del cambio climático y mitigar sus efectos adversos.

Que la Ley 697 de 2001, por la cual se fomenta el uso racional y eficiente de la energía y se promueve la utilización de energías alternativas y su Decreto Reglamentario 3683 de 2003, promueven el uso racional y eficiente de la energía y demás formas de energía no convencionales, de tal manera que se tenga la mayor eficiencia energética para asegurar el abastecimiento energético pleno y oportuno, la competitividad de la economía colombiana, la protección al consumidor y la promoción de fuentes de energía no convencionales, de manera sostenible con el medio ambiente y los recursos naturales.

Que además, la Ley 697 de 2001, declaró asunto de interés social, público y de conveniencia nacional, el uso racional y eficiente de la energía, así como el uso de fuentes energéticas no convencionales. De esta misma manera, definió el uso eficiente de la energía como la utilización de la energía, de tal manera que se obtenga la mayor eficiencia energética, bien sea de una forma original de energía y/o durante cualquier actividad de producción, transformación, transporte, distribución y consumo de las diferentes formas de energía, dentro del marco del desarrollo sostenible y respetando la normatividad, vigente sobre medio ambiente y los recursos naturales renovables.

Que la Ley 1715 del 13 de mayo de 2014, por la cual se regula la integración de las energías renovables no convencionales al sistema energético nacional, tiene por objetivo, promover la utilización de las fuentes no convencionales de energía, principalmente aquellas de carácter renovable, en el sistema energético nacional, así como promover la gestión eficiente de la energía, que comprende tanto la eficiencia energética como la respuesta de la demanda, de manera, que declaró este asunto como de utilidad pública e interés social, público y de conveniencia nacional, fundamental para asegurar la diversificación del abastecimiento energético pleno y oportuno, la competitividad de la economía colombiana, la protección del medio ambiente, el uso eficiente de la energía y la preservación de los recursos renovables.

Que en consecuencia, la referida Ley de manera expresa preceptúa: "*Esta clasificación de utilidad pública o interés social tendrá los efectos oportunos para su primacía en todo lo referente a ordenamiento del territorio, urbanismo, planificación ambiental, fomento económico, valoración positiva en los procedimientos administrativo de concurrencia y selección, así como a efectos de expropiación forzosa.*"

Que el desempeño energético de las edificaciones se evalúa en términos de fuente de energía, consumo energético, y perdidas por generación y transmisión. Es por eso que para el mejoramiento de la eficiencia energética se hace necesario potenciar las oportunidades de conservación de energía e implementando las estrategias desde la planeación hasta la operación.

Que en la valoración de disminución en consumo energético por potencia instalada, se establece como referencia la carga mínima dispuesta para cálculo de los circuitos alimentadores, ramales y acometidas. Sin embargo, el ahorro se calcula con base en la carga diversificada dependiendo del uso de la edificación, y por su parte, la línea base sobre la cual se calcula la disminución de consumo energético, debe ser el resultado de la suma total de cargas diversificadas para aparatos, con el consumo máximo permitido por las normas y reglamentos técnicos.

Que en lo que concierne al uso de la energía en la ciudad capital, se estimó para el año 2012 un consumo de 9.195 GWh de energía eléctrica, 967.9 millones de m^3 de gas natural, 62 millones de kilogramos de GLP, 280 millones de galones de gasolina, 219 millones de galones de ACPM, 102.500 toneladas de carbón mineral, 15.9 millones de galones de fuel oil, 19.7 millones de otros derivados del petróleo y 227.718 galones de Jet fuel.

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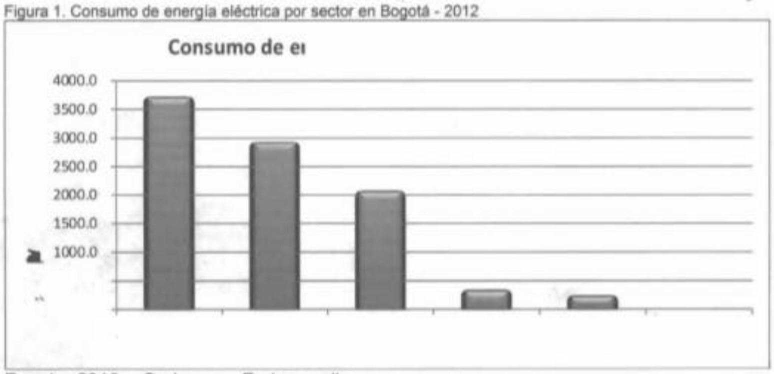
Que en energía eléctrica se identificó al sector residencial como el de mayor consumo con 3.699 GWh/año, lo cual representa una participación del 40,2%, seguido por el sector comercial con 31,6% e industrial con 22,3%, los sectores restantes consumen el 5,8%. Ver figura 1.

Figura 1. Consumo de energía eléctrica por sector en Bogotá - 2012



Fuente: 2013 – Codensa – Fedesarrollo

Que en la figura 2 se observa la participación del consumo energético para cada sector; es así, como el sector de mayor diversidad del uso de energéticos es el industrial, en el sector residencial el gas licuado de petróleo- GLP es el de menor consumo y, los consumos de electricidad y gas natural son de similar participación; para el caso del sector comercial, el energético de mayor uso es la energía eléctrica, seguido por el gas natural y en menor proporción el gas licuado de petróleo GLP; el sector industrial consume principalmente electricidad y gas natural seguido por carbón, fuel oíl, diésel y otros derivados; el sector oficial principalmente usa gas natural y electricidad, alumbrado público usa exclusivamente energía eléctrica; y el sector transporte consume gasolina seguido por el uso de ACPM y bajo consumo de gas natural.

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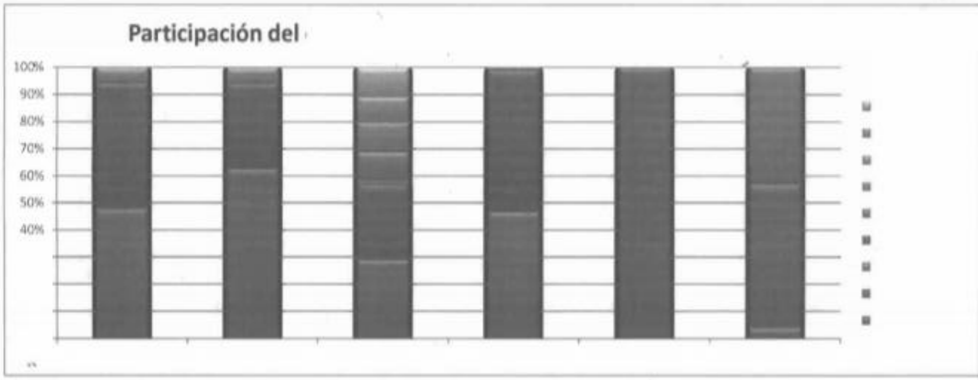
Figura 2. Participación del consumo de energéticos por sector en Bogotá – 2012



Fuente: 2013 –SDA.

Que en lo referente al consumo eléctrico por iluminación de vallas tubulares comerciales, se tiene que en la ciudad de Bogotá se cuenta con un registro de instalación de 1.027 vallas publicitarias tubulares (corte de 31 de enero de 2016), se realizó notificación de 1.000 de estos elementos, algunas de cara sencilla y otras de doble cara, por lo tanto, es esta la cantidad de vallas que se utiliza para las estimaciones de consumo por iluminación:

Tabla 1. Consolidado vallas comerciales tubulares a enero de 2016

TOTAL DE REGISTROS OTORGADOS	TOTAL DE REGISTROS OTORGADOS_INSTALADOS	TOTAL REGISTROS OTORGADOS	TOTAL REGISTROS OTORGADOS	PORCENTAJE DE VALLAS ILUMINADAS

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		E INSTALADOS UNA CARA	E INSTALADOS DOS CARAS	(dato muestra en campo)
1027	1000	124	876	90%

Que de acuerdo a información técnica recolectada en campo, se estima que un 90% de la vallas están dotadas con iluminación, el restante 10% no presenta esta característica, principalmente por razones de seguridad. De igual manera, las vallas que cuentan con iluminación, generalmente utilizan tres (3) reflectores para brindar luz a toda el área útil publicitaria de cada cara de la valla; en este sentido, al conocer la cantidad de vallas que presentan cara sencilla y doble cara y conociendo la cantidad de reflectores por cara se logra un cálculo de reflectores totales utilizados, que es un dato básico para estimar un consumo eléctrico.

Tabla 2. Cantidad de caras de vallas comerciales tubulares a enero de 2016

A	B	C	D	[(A*C)+(B*C)]*D
TOTAL CARAS DE VALLAS INSTALADOS MODO "UNA CARA"	**TOTAL CARAS DE VALLAS INSTALADOS MODO "DOBLE CARA"**	**CANTIDAD REFLECTORES UTILIZADOS POR CARA**	**PORCENTAJE DE VALLAS QUE UTILIZAN ILUMINACIÓN**	**CANTIDAD TOTAL REFLECTORES UTILIZADOS**
124	876	3	90%	2700

Que un reflector típico utilizado para iluminación de vallas publicitarias, tiene una potencia de 300 Watts y se activan mediante sensores de luz, esto indica que cada reflector puede estar encendido cerca de 11 horas en la jornada (entre las 6:30 p.m. y las 5:30 a.m.) promedio de horas de sin luz natural en la ciudad.

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A	B	C	(A*B*C)/1000
CANTIDAD TOTAL REFLECTORES UTILIZADOS	**CONSUMO ELÉCTRICIDAD POR REFLECTOR (W/h)**	**CANTIDAD HORAS DE ENCENDIO EN JORNADA**	**CONSUMO ESTIMADO DE ELECTRICIDAD kW/h**
2700	300	11	8910

Que se estima que la cantidad de electricidad consumida por los reflectores que iluminan las vallas tubulares comerciales en la ciudad, asciende a 8910 kW/h (kilovatios hora), conforme a los datos asumidos de potencia media de los reflectores utilizados y la información que reposa en el área de Publicidad Exterior Visual de la SCAAV.

Que por otra parte, pese a representar una inversión inicial mucho más alta, se están dando situaciones de sustitución de reflectores tradicionales por reflectores LED, los cuales pueden representar una reducción de 2/3 partes del consumo, situación que de presentarse en todas las vallas de la ciudad (el uso de reflectores LED) representaría ahorros de energía eléctrica cercanos a los 6000 kWh por jornada que al año será cerca de 1 GWh (gigavatio/hora), al considerar ocupación de tiempo completo de todas las vallas actualmente instaladas.

Que de aplicarse restricciones al tiempo máximo u horario autorizado para tener iluminadas las vallas tubulares, la reducción del consumo respecto al escenario base, sería proporcional al porcentaje de horas en que se reduzca el tiempo de iluminación.

Que de igual manera, existen en el Distrito Capital elementos menores de publicidad exterior visual PEV, que pueden ser de varios tipos, entre los cuales se encuentran: aviso en fachada, aviso divisible, aviso tipo canopy, aviso nombre edificio, elemento en espacio público, mural artístico o panel publicitario.

ALCALDÍA MAYOR DE BOGOTÁ, D.C.

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Que no todos los elementos menores de PEV tienen iluminación, sin embargo según su tipo se puede establecer tanto la presencia o no de iluminación, como la cantidad de horas que está encendida esta iluminación. De un total 4444 registros otorgados para la instalación elementos menores de PEV, se tienen una cantidad de 2066 avisos iluminados que generalmente usan bombillas ahorradoras o reflectores de 75 Watios, por lo tanto es esta la cantidad se utiliza para las estimaciones de consumo por iluminación.

A	B	C	(A*B*C)/1000
CANTIDAD TOTAL DE BOMBILLAS EN ELEMENTOS MENORES PEV	**CONSUMO ELÉCTRICIDAD POR BOMBILLA (W/h)**	**CANTIDAD HORAS DE ENCENDIO EN JORNADA**	**CONSUMO ESTIMADO DE ELECTRICIDAD kW/h POR JORNADA**
4200	**75**	**6**	**1890**

Esto representa un consumo de cerca de 700 MWh en un año, el potencial de ahorro es proporcional a la cantidad de horas a lo que se restrinja el encendido.

Que mediante boletín IFN febrero 16 de 2016, de la página web del IDEAM, establece frente a las precipitaciones, que en la región andina la condición entre moderada y altamente deficitaria se extenderá a toda la región, una probabilidad del 54%, mientras que el 28% es de probabilidad que las lluvias llegasen a tener un comportamiento climatológico normal y 18% por encima de los valores medios históricos.

Que el Gobierno Nacional ha iniciado una cruzada para incentivar el ahorro de energía en los hogares y empresas colombianos y así evitar "cortes de energía y un racionamiento" por tanto, llamó a los miembros del Consejo Gremial Nacional, a los alcaldes y gobernadores del país para que se sumen a ella, todo por cuenta de que las lluvias en el país han sido las más bajas y las temperaturas las más altas de los últimos años a causa del fenómeno climático de El Niño,

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aunado a la pérdida del 11% de la capacidad de generación eléctrica en las últimas semanas debido a un incendio que afectó la Central Hidroeléctrica de Guatape, en el oriente antioqueño y a un daño en la térmica Termoflores, en el Caribe por lo que la nación entró en una crisis energética.

Que la política ambiental colombiana tiene como principios generales consagrados en el artículo 1° de la Ley 99 de 1993, el de desarrollo sostenible contenidos en la Declaración de Río de Janeiro de junio de 1992 sobre Medio Ambiente y Desarrollo, así como el principio de precaución conforme al cual, cuando exista peligro de daño grave e irreversible, la falta de certeza científica absoluta no deberá utilizarse como razón para postergar la adopción de medidas eficaces para impedir la degradación del medio ambiente.

Que bajo la misma línea, el citado artículo establece que la acción para la protección y recuperación ambientales del país es una tarea conjunta y coordinada entre el Estado, la comunidad, las organizaciones no gubernamentales y el sector privado.

Que en procura de aliviar tan extrema situación el gobierno dispuso de varias medidas como incentivar el ahorro de energía; aplicar castigo a quienes aumenten el consumo y derrochen; conceder compensaciones a empresas que generen su propia energía; invitar a las empresas privadas a bajar el consumo en horas piso y apagar las luces en los edificios públicos a partir de las 6:00 p.m.

Que el sector público del Distrito capital en atención al llamado del Presidente Santos se vincula a esta campaña de ahorro de energía en vía de disminuir el consumo de energía en el Distrito Capital, por ende, se hace necesario dictar lineamientos para generar estrategias de ahorro de energía eléctrica en la ciudad capital, sin perjuicio de aquellas dictadas en la Circular 20 del 9 de marzo del año en curso expedida por la Secretaría General de la Alcaldía Mayor.

En mérito de lo expuesto,

ALCALDÍA MAYOR
DE BOGOTÁ, D.C.

Por medio del cual se establecen medidas transitorias y lineamientos ambientales para promover el ahorro de energía eléctrica en la ciudad de Bogotá, D.C."

DECRETA

Artículo 1.- Objeto. Establecer medidas transitorias y lineamientos ambientales para promover el ahorro de energía eléctrica en la ciudad de Bogotá, D.C., las cuales permanecerán mientras existan las condiciones que dan lugar a la expedición del presente decreto, las cuales se encuentran contenidas en los considerandos del mismo.

Artículo 2.- Ámbito de Aplicación. Las disposiciones del presente decreto obligan a las entidades del sector central, descentralizado funcional o por servicios, las localidades del Distrito Capital y a los titulares de permisos, registros o autorizaciones ambientales que versen sobre vallas comerciales tubulares y avisos menores de Publicidad Exterior Visual.

Se exceptúan del cumplimiento de las medidas transitorias los establecimientos de salud, educación y aquellas actividades que comprendan la prestación de servicios públicos esenciales que necesariamente se deben seguir prestando.

Artículo 3.- Medidas Transitorias. Establecer como medidas transitorias, las siguientes:

a. Apagar las luces, equipos de cómputo, impresoras, sistemas de aire acondicionado de las Sedes Administrativas del sector central, descentralizado funcional o por servicios del Distrito Capital, a partir de las 6:00 p.m. siempre que no se afecte la continuidad de las actividades que de manera necesaria deban seguirse desarrollando.

b. Restringir la iluminación en vallas comerciales tubulares, a partir de las 08:00 pm y hasta las 6:00 a.m.

c. Restringir la iluminación de avisos menores, a partir de las 08:00 p.m. y hasta las 6:00 a.m.

ALCALDÍA MAYOR
DE BOGOTÁ, D.C.

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Artículo 4.- Lineamientos. Implementar dentro de la estructura administrativa de Bogotá, sector central, descentralizado funcional o por servicios y en las localidades del Distrito Capital, los siguientes lineamientos para generar estrategias de ahorro de energía eléctrica:

1) Promover campañas en buenas prácticas y cambio de hábitos para uso de escaleras, manejo de la iluminación, computadores, consumos de agua y sistemas de bombeo, en medios masivos de comunicación y dirigida a todo el sector comercial, público y de servicios.

2) Procurar horarios de trabajo que aprovechen la iluminación natural.

3) Fortalecer la capacidad en los profesionales de arquitectura e ingeniería en diseños de sistemas de iluminación, refrigeración y aire acondicionado eficiente.

4) Realizar campañas de información y capacitación en las entidades oficiales en la aplicación de los decretos y resoluciones de sustitución y uso de fuentes lumínicas de alta eficiencia en las edificaciones del sector público.

5) Verificar permanentemente los niveles de iluminación, mejoramiento del servicio y del mantenimiento de luminarias de cada una de la sedes.

6) Optimizar el consumo de energía eléctrica en alumbrado público con nuevas tecnologías en fuentes y luminarias.

7) Realizar proyectos demostrativos para lograr autonomía energética con fuentes renovables y presentar a la Secretaria Distrital de Ambiente los resultados de los mismos.

8) Mejorar los esquemas de mantenimiento, operación y compra de energía para el alumbrado público con énfasis en el servicio, la eficiencia energética y la eficiencia financiera para el distrito, con la vinculación de nuevos operadores y actores.

ALCALDÍA MAYOR
DE BOGOTÁ, D.C.

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9) Cambiar las bombillas incandescentes por bombillas ahorradoras, específicamente el cambio de luminarias a LFC (Lámparas Fluorescentes Compactas), garantizando una eficiencia apreciable con adecuados niveles de iluminación y menos consumo de energía eléctrica.

Artículo. 5.- Seguimiento. La Secretaría Distrital de Ambiente efectuará el seguimiento a las medidas transitorias establecidas en el artículo 3 respecto de la disminución de consumo energético mediante los Planes Institucionales de Gestión Ambiental PIGA.

Artículo 6.- Sanciones. El incumplimiento de las medidas transitorias por parte de los titulares de permisos, registros o autorizaciones ambientales que versen sobre vallas comerciales tubulares y avisos menores de Publicidad Exterior Visual, dará lugar a la imposición de sanciones administrativas ambientales contempladas en la Ley 1333 de 2009.

Artículo 7.- Publicidad. Las Entidades del Distrito Capital deberán a su interior efectuar campañas de divulgación y socialización, a fin de concientizar a todos los usuarios de energía sobre las prácticas de reducción del consumo hasta alcanzar una cultura de apropiación, autorregulación y correcto uso que se haga de los sistemas de iluminación y climatización.

Artículo 8.- Vigencia. El presente Decreto rige a partir de la fecha de su publicación en el Diario Oficial.

PUBLÍQUESE, COMUNÍQUESE Y CÚMPLASE.

Dado en Bogotá, D.C., a los 16 MAR 2016

ENRIQUE PEÑALOSA LONDOÑO
Alcalde Mayor

ALCALDÍA MAYOR
DE BOGOTÁ, D.C.

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FRANCISCO JOSÉ CRUZ PRADA
Secretario Distrital de Ambiente

Proyectó: María Concepción Osuna/Funcionaria SDA
Revisó: Viviana Carolina Ortiz/Directora Legal SDA
Andrea Cortés/ Directora de Control Ambiental SDA
Aprobó: Carlos Arturo Puerta Cárdenas. Subsecretario General y de Control Disciplinario SDA
Dalila Astrid Hernández/Secretaria General Alcaldía Mayor

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