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Technical and Economical Evaluation of Combined Cooling, Heat and Power Technology: A Brazilian Study Case Considering Different Consumers

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Dissertação apresentada ao Programa de Pós-Graduação em Engenharia Elétrica da Universidade Federal de Juiz de Fora, na área de concentração em Sistemas de Energia Elétrica, como requisito parcial para obtenção do título de Mestre em Engenharia Elétrica.

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ABSTRACT

The world is trying to move to a cleaner energy environment, especially on the electricity generation sector, which is responsible for a large share of CO_2 emissions. In Brazil, renewable energy sources are responsible for a great part of the electricity generation, but current changes in the Brazilian climate brought a necessity of diversification on the energy matrix. Then, distributed generation is a good way to diversify the Brazilian power matrix. Considering that cogeneration systems are distributed generation, and Brazilian buildings have need of cooling, due to the warm weather, the use of cogeneration equipped with an absorption or adsorption chiller could be beneficial. The trigeneration system is a highly efficient process, which can produce electricity, heating and cooling from the same primary energy source. However, there are really few researches concerning trigeneration systems in Brazil, especially on small and micro plants. Thus, this thesis will make and provide a technical and economical evaluation of small and micro trigeneration systems to different buildings under distinct tariff policies in Brazil. To do so, this work will optimize the sizing and monthly schedule the dispatch of the trigeneration systems to each one of the four study cases. Then, it will evaluate the maximum net present value (NPV) considering the variation of discount rate and US Dollar conversion rate. In the sequence, the grid dependence index (GDI), the discounted payback, the levelized cost of energy (LCOE) and the primary energy ratio (PER) to the best NPVs will be presented and analysed. As a result, this thesis will show that trigeneration plants can be profitable and can be certainly an efficient way to adopt a reliable and controllable distributed generation. Also, it will prove that it is possible to find situations in which the trigeneration plant can offer a high primary energy ratio, a fair levelized cost of energy, and in the meantime, it can provide financial savings with fair payback time in Brazilian buildings.

Keywords: 1. energy resources optimization. 2. small and micro trigeneration. 3. CCHP. 4. distributed power generation.

RESUMO

O mundo está tentando mudar para um ambiente de energia mais limpa, especialmente no setor de geração de eletricidade, que é responsável por uma grande parcela das emissões de CO_2. No Brasil, fontes renováveis são responsáveis por grande parte da geração de eletricidade, mas mudanças atuais no clima brasileiro trouxeram uma necessidade de diversificação na matriz energética. Logo, a geração distribuída é uma boa maneira de diversificar a matriz energética brasileira. Considerando que os sistemas de cogeração se enquadram na geração distribuída, e que os prédios brasileiros necessitam de resfriamento, devido ao clima quente, o uso de cogeração adicionado à um chiler de absorção ou adsorção pode ser muito útil. O sistema de trigeração é um processo altamente eficiente, que pode produzir eletricidade, aquecimento e resfriamento a partir da mesma fonte de energia primária. No entanto, existem poucas pesquisas sobre os sistemas de trigeração no Brasil, especialmente em pequena e micro escala. Assim, esta dissertação fará uma avaliação técnica e econômica de sistemas de micro e trigeração para diferentes edifícios sob políticas tarifárias distintas no Brasil. Para tanto, este trabalho otimizará o dimensionamento e o cronograma de despacho mensal dos sistemas de trigeração para cada um dos quatro estudos de caso. Em seguida, avaliará o valor presente líquido máximo (VPL) considerando a variação da taxa de desconto e da taxa de conversão do dólar norte-americano. Na sequência, o índice de dependência da rede (GDI), o *payback* descontado, o custo nivelado da energia (LCOE) e a razão da energia primária (PER) para os melhores VPLs serão apresentados e analisados. Como resultado, esta dissertação mostrará que as plantas de trigeração podem ser lucrativas e certamente ser uma maneira eficiente de utilização de uma geração distribuída confiável e controlável. Além disso, provará que é possível encontrar situações em que a planta de trigeração possa oferecer uma alta taxa de energia primária (PER), um adequado custo de energia nivelado (LCOE) e, ao mesmo tempo, pode proporcionar economia financeira com tempo de retorno razoável em edifícios brasileiros.

Palavras-chave: 1. otimização de recursos energéticos. 2. pequena e micro trigeração. 3. CCHP. 4. geração distribuída de energia.

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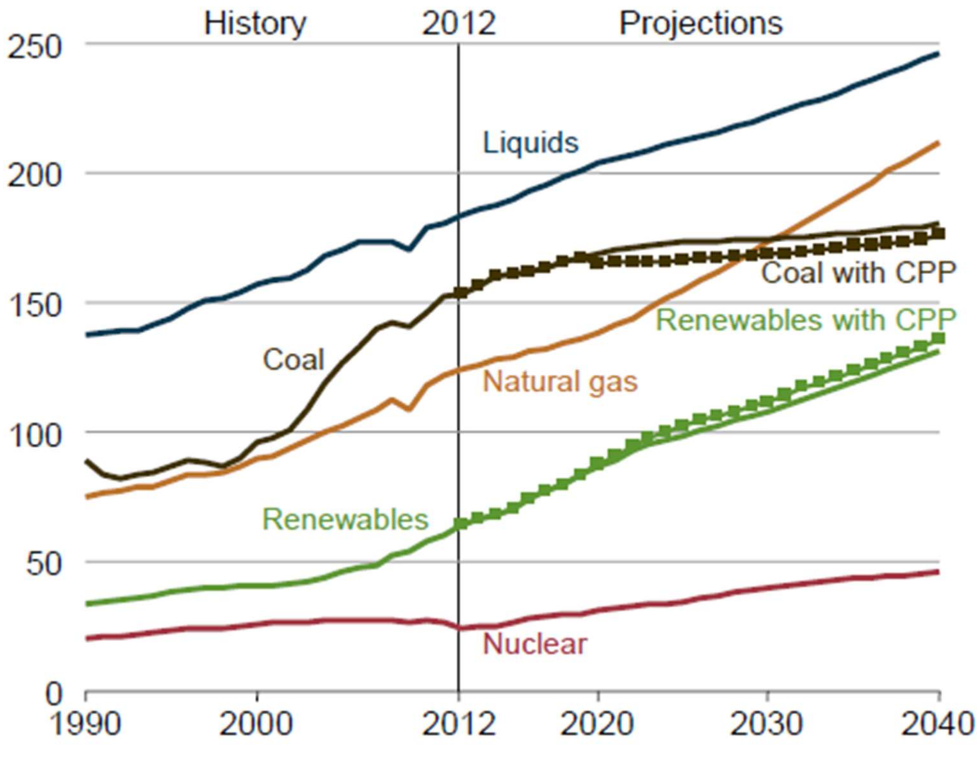
SUMMARY

1. INTRODUCTION

An usual effect of the economic development is the rise in the energy demand. According to [1], a considerable increase in worldwide demand for energy began in 2012 and will continue until 2040. In 2012 the world energy consumption was 549 quadrillion British thermal units (Btu) and the projection for 2040 is a utilization of 815 quadrillion Btu, representing a 48% increase on the period and 1.4% increase per year. Figure 1 shows historical data and projections to world energy consumption by energy source. It projects a fast expansion on renewable energy sources (2.6% per year) and nuclear energy (2.3% per year), while coal increases only 0.6% per year. After all, the report presents a reference case where non-fossil sources will grow, but fossil fuels will still be the main source of energy in the world, corresponding to 78% of energy consumption in 2040.

Figure 1 – World energy consumption by energy source (quadrillion Btu)[1]



Source: [1]

Also, according to [1], the electricity consumption by end users is the type of delivered energy that grows faster, leading to an average increase of 1.9% per year on electricity generation from 2012 to 2040. In 2012, fossil fuels provided 67% of electricity generation,

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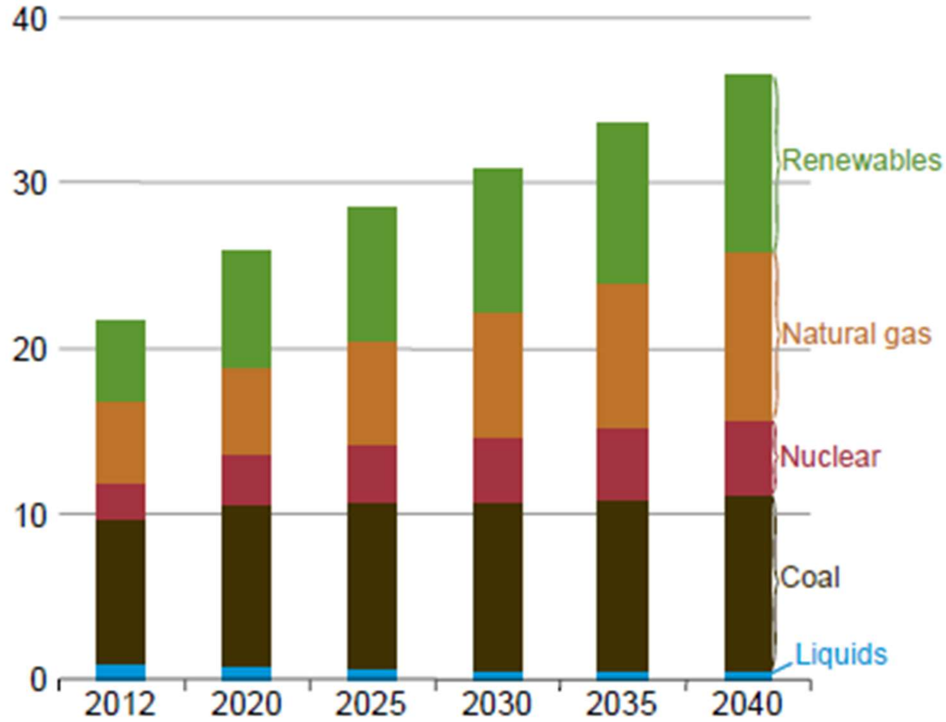
[1] Dashed lines show effects of U.S. Clean Power Plan (CPP)

while in 2040 it will provide 59% of electricity. The decrease on fossil fuel use to electricity production is due to investments on renewable energy sources, mainly hydropower and wind power generation. Therefore, renewable electricity production grows from 22% in 2012 to 29% in 2040, and coal share reduces from 40% in 2012 to 29% in 2040. In general, the projected share of renewable, natural gas and coal will be similar in 2040, around 29%. Figure 2 shows the historical data and projections to electricity generation by source.

Figure 2 – World electricity generation by energy source (trillion kilowatt hours)



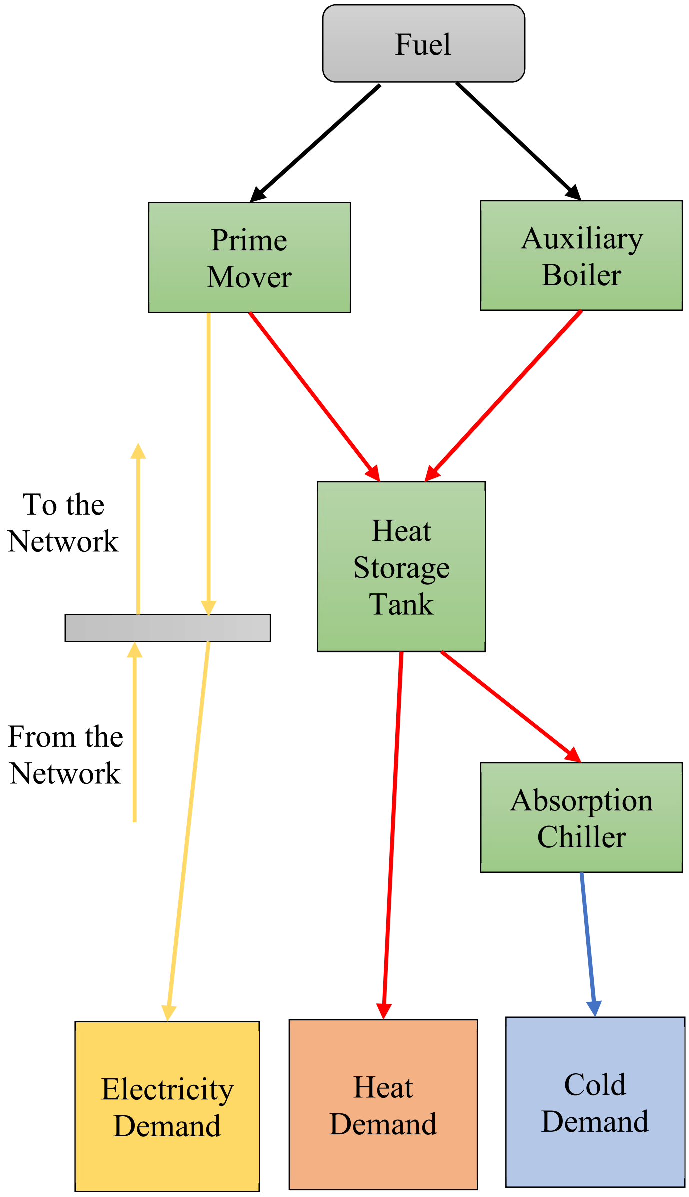
Source: [1]

Thus, the world is trying to move to a cleaner energy environment, especially on the electricity generation sector, which is responsible for a large share of CO_2 emissions. One of the main streams of change is coming from distributed generation (DG), with adoption of new sustainable and lower carbon technologies like photovoltaic, wind and combined heat and power plants (CHP) [2]. The DG adoption has some advantages such as reduced transportation losses [2,3,4], renewable primary energy source, like wind and solar [2]. Also, it can help to lower carbon emissions on electricity and heating with increased conversion efficiency, which is the case of highly efficient CHP [4,5,6] or combined cooling, heat and power plants (CCHP) [3]. Moreover, DG plants can stimulate fuel diversification and energy autonomy, and can also increase the power quality and reliability in the network [2,4,6,7]. However, a network with great insertion of DG would need an improved structure and operation to guarantee network stability [3].

In the present work the trigeneration system is the studied subject, thus the main components of this system will be presented. Also, as most part of trigeneration plants or CCHP are the same of cogeneration systems or CHP, the last one will be presented first followed by the CCHP plant. A CHP plant is usually composed of a prime mover (e.g. gas turbine, steam turbine, reciprocating engine, fuel cell, among others), the core of the plant, which uses fuel as primary energy source to produce electricity and heat. Also, when the prime mover does not generate sufficient heat to fulfil the demand, an auxiliary boiler is used to complement the required heat energy. In addition, it is usual to have a heat storage tank to aggregate the heat from the prime mover and from the auxiliary boiler. Therefore, when a thermally activated technology such as absorption or adsorption chiller is added to the CHP plant, it becomes a trigeneration plant, which also produces cold energy [8,9]. Figure 3 shows a usual flowchart of a trigeneration plant.

Cogeneration and trigeneration systems have been studied for different purposes. In the first place, there are studies considering optimisation of single CCHP systems which minimize the plant costs, pollution and primary energy savings with the use of solar, wind power and fuel cells [10]. While others optimise, or evaluate, the collective use of different, or similar, micro-CHP plants to improve the quality and reliability of microgrids, or the local distribution network [11,12,13,14]. Although, this thesis will focus in the optimisation of small-scale and micro-scale CCHP systems, it does not consider the network, and focus more on the policy and economic point of view of Brazilian buildings.

Figure 3 – Usual trigeneration system



Source: Author

1.1 BRIEF LITERATURE REVIEW

This section presents papers that give reasons and support to the research proposed. It starts presenting large CHP and CCHP systems and then it moves to small and micro CHP/CCHP systems, which is the focus of this thesis.

An approach that evaluates the energy price policies effects on optimal configuration of cogeneration and trigeneration in Iran under conditions of selling and not-selling electricity to the utility is presented by [15]. So, a particle swarm optimization algorithm was used to minimize the cost of buying and operating various CHP and CCHP systems (i.e. plants with different prime movers, such as gas turbine, microturbine and reciprocating engine) in an industrial dairy unit. After all, the paper determined that the choice of prime mover plays an important role in the economic feasibility of the CHP and CCHP systems; similarly, the economic benefit was considerably dependent on optimal sizing and operating conditions of cogeneration and trigeneration plants; as well as, the use of such systems was effective in lowering total primary energy consumption; the research considered the reciprocating engine as the best prime mover option; in addition, it was proved that with the 2010 energy price policies in Iran, the CCHP plants were more economically feasible than their CHP counterparts, however, the 2010 Iran policies retarded promotion of such systems; as a final statement, the authors declared that the policy of selling electricity to utility is prerequisite to successful widespread utilization of these plants.

Another work displayed an optimal operation of hybrid power systems including renewable sources in the Brazilian sugarcane industry [16]. The control structure had to schedule the production of electricity, according to contract rules, and had to produce flows of steam in different pressures to the industry process of ethanol and sugar production. Therefore, it had to control three renewable sources of energy: photovoltaic, wind and the cogeneration from biomass. Also, the proposed control algorithm had to maximise the use of renewable energy sources, maximise the gains of the boilers, manage the use of energy storages and supply the defined amount of energy. From the simulation results the authors concluded that a satisfactory operation of the proposed control structure was observed.

In [17] is proposed a method to assess the stability of distributed systems with synchronous generators under load variations. To do so, a mathematical model of the distribution system with synchronous generators was proposed on the paper to be used for practical stability studies. Therefore, sufficient conditions for the power distribution system, described as a switched affine system, to be practically stable with respect to the operating security region were given in the form of matrix inequalities constraints. To test the proposed method and mathematical model, a typical arrangement of a distributed system with synchronous generation was used, which is usually viewed in cogeneration plants in the sugarcane industry of Brazil. To conclude, the paper declared that the proposed method guarantees a stable operation for a single distributed generation operating connected to a feeder with varying loads.

A risk constrained portfolio selection of renewable sources in hydrothermal electricity markets in Brazil was presented in [18]. So, a mathematical model was developed to explore the seasonal complementarity of a biomass cogeneration power plant together with a small hydro unit generation patterns. Also, the paper proposed a method that aims at composing an optimal portfolio of these two sources, and jointly determines the risk-constrained optimal trading strategy for an energy trading company in the forward contract market. The model was based on two-stage stochastic programming and it was solved through its linear programming deterministic equivalent. In summary, results showed that the model maximized the revenue of an energy trading company, while mitigating hydrological and fuel unavailability risks; also, it provided safe and competitive firm energy delivery over a given time horizon.

In the light of sugarcane industry sector, once more, in [19] there was a discussion of the economic viability of electricity cogeneration using sugarcane bagasse for sale of surplus electricity for concessionaires through the Brazilian electricity interconnected system. The authors concluded that the cost of production was a competitive value compared to other small power plants, which made it an excellent alternative both for the company's financial complementarity, as well as, for the production of electricity of the plant, with environmental and socioeconomic advantages.

As shown before, large CHP and CCHP systems are studied with different approaches inside and outside Brazil. Also, Brazilian studies focus on the biomass industry, mainly sugarcane industry, and in cogeneration systems. From now it will be presented small and micro scale cogeneration and trigeneration systems studies.

An investigation was performed in a micro-CHP unit with 6kW nominal electric output during a 24h test in which was applied a realistic daily load profile of an Italian residential non-HVAC electric demand. Also, the micro-CHP unit was operated via electric load-following control strategy. Then, the data was compared to results from a residential building connected to the network and with heat coming from a natural gas boiler. To evaluate the results, it was performed an energy, exergy, and environmental analyses. In that case, the micro-CHP unit allowed a reduction of 2% on CO_2 emissions, while using 3.2% more primary energy [4].

This time, an energy and CO_2 emissions performance assessment of residential micro-CHP systems with dynamic whole-building simulation programs was performed in [20]. The assessment identified important parameters influencing the performance of micro-CHP systems, and evaluated a number of micro-CHP systems for several buildings types, occupant related loads and network electricity mixes (i.e. European electricity mix, and combined power plant mix). In the sequence, the paper compared the results with traditional condensing boilers and heat pump technologies. Therefore, the study revealed that in certain circumstances, micro-CHP systems can significantly reduce primary energy consumption and CO_2 emissions relative to conventional means of supplying heat and power. The paper affirmed however that micro-CHP systems face strong competitive environment when combined cycle power plant mix with heat pump technology (or other innovative supply options) is adopted. Also, the authors highlighted that the micro-CHP unit has to be correctly dimensioned, in accordance with the heat loads, in order to fully exploit the reduction potential.

In [21] an evaluation of the dynamic effect of prime movers in trigeneration systems was made for high-rise building applications across four types of prime movers: diesel engine, gas engine, gas turbine with recuperator, and combined gas turbine cycle. The paper analysed the energy and environmental performances of those prime movers. Also, it was conducted under changing climatic and loading conditions in a year. Then the results were compared to conventional methods. To implement the building zones, the equipment design and simulate one year of activity, the authors used the software TRNSYS[2]. The authors declared that when it is considered the primary energy savings compared to the traditional provisions of cooling, heating and power, the best prime mover was the diesel engine; however, when it is considered the annual carbon dioxide reduction, the best one was the combine gas turbine cycle; although, when it is considered the combination of energy merit and the system simplicity, the trigeneration systems primarily moved by gas engine was chosen to be the best option among the four options; additionally, the paper observed that the energy performance of the prime mover depended on its part-load efficiency in response to the changing loading and climatic conditions, while, the carbon emissions were related to both, its energy performance and fuel type.

Another work studied an operation optimization model for micro-turbine based CCHP systems [22]. It considered the electricity spot price (variable) and an interactive mode with the network. The micro-turbine was modelled on Matlab/Simulink and then it was applied into the operation optimization model. Also, the optimization aim was to minimize the system operating cost. To finalise, the regional load and the effects of electricity variation prices on the operation were analysed. The authors declared that the operation of the CCHP system was more economical than the decentralised system, particularly when there was a great difference

[2] TRNSYS is a graphically based software that simulates behaviour of transient systems, such as thermal and electrical energy systems, but not limited to it [51].

between the load of the CCHP system and the regional load; although, when the electricity price was low, the economic advantage disappeared; they also affirmed that peak-valley pricing policy worked well when the peak and valley of regional load matched the peak and valley of the electricity price, otherwise, the peak-valley pricing policy can probably increase the peak-valley difference; moreover, they attested that CCHP systems became source of peak regulation under spot price, so it can reduce the pressure during peak-valley load, as well as, regional load curve can be optimized; finally, they concluded that the pricing policy is very important in optimizing the operation of the power network.

In the sequence, the paper studied the integration of a hybrid CCHP system into a commercial building considering renewable and non-renewable sources of energy [23]. The study considered three objective functions, cost saving, energy saving and emission reduction. In order to find the best size of the system components, each objective function was considered as a single optimization problem to be solved via genetic algorithm. Then, it was used an analytic hierarchy process to determine the most profitable answer from the previous optimization process. The authors made two different analyses, the first one was the separated optimization process, and the second was with utilization of the analytic hierarchy process. In the separated analysis, the annual operating cost ratio method had more than 57% of annual operating cost savings, at the same time, the energy saving and emission reduction was not substantial; moreover, on the primary energy saving ratio and carbon emission reduction ratio optimization the savings/reduction were considerable and almost similar, however, the value of cost saving was shortened. Considering the analytic hierarchy process, the paper affirmed that the primary energy saving ratio was ranked as the best option between the three optimization methods. It also pointed out that the number of photovoltaic and thermal panels on the three optimization processes were found at their maximum allowable value, which asserted the importance of solar panels in the performance and structure of the CCHP system. As a general conclusion, they declared that the advantages of the CCHP system utilization were clear, and it can bring significant economic profits and also can ease the energy savings and CO_2 emissions reductions.

A novel thermal storage strategy for CCHP system based on energy demands and state of storage tank was presented in [24]. So, the operational state of the power generation unit was based upon electric demand, thermal demand and the state of thermal storage. As well as, the paper described the operation principle of the thermal storage strategy and compared it with traditional strategies. The final action was the use of a hospital in China to evaluate and compare the performance of the system operating under different storage strategies. To conclude, the authors declared that the proposed method can make both, power generation unit and capacity of thermal storage tank, be fully used by CCHP systems, thus, more improvement in performance of trigeneration system on economic, environmental, and energy aspects can be achieved; however, they affirmed that the effect of the proposed storage operation method differ under different operation strategies; also according to the authors, the best option to the hospital was to use a mix of thermal-led strategy and the proposed thermal storage strategy to major energy conservation.

In [25] a novel optimal operational strategy for the CCHP system based on two operating modes was presented. Thus, the whole operating space of the trigeneration system was divided into several regions by border surfaces, which were decided by an integrated performance criterion. Not to mention, the performance criterion was based on primary energy consumption, carbon dioxide emissions and operational cost. Based on the previous defined regions, the operating schedule of the trigeneration was chosen between electrical-led and thermal-led mode. To assess the effectiveness and performance of the proposed method, a reference CCHP system was modelled for a hypothetical hospital in China and compared to a separated production system, not to mention, the hourly energy requirements of the building were calculated via EnergyPlus[3] program. The paper concluded that the proposed strategy based on integrated performance criterion was better than the separated production; also, the new strategy can effectively balance the influences of fuel consumption, operating costs and emissions; furthermore, the proposed method can flexibly characterize the effects from policies and market variations by adjusting its weight coefficients; although, it did not consider part-load operation efficiency, yet, those parameters were considered in the method, so it is possible to improve the performance of the presented strategy if part-load efficiency is also considered.

According to [2], a micro-CHP system is easily controlled and is commonly coupled to heat storage systems, which creates a flexibility on the power generation. Therefore, the paper analysed the potential of micro-CHP flexibility on its operation. To do so, a micro-CHP system was evaluated to a demand response control strategy applied to real-time pricing system. Then, the energy costs for households using the proposed control strategy was compared to standard thermal-led control strategy. In the final analysis, the use of demand

[3] EnergyPlus is a whole building energy simulation program that is used to model both energy consumption and water use in buildings [50].

response strategy on the considered real-time pricing system can save up to 14% in energy costs for households. The authors highlight that the amount of savings does not provide a strong economic incentive to individual households invest on micro-CHP with the proposed demand response control strategy, although, it depends on particular energy prices and situations.

The optimization of a micro-CHP system in a real-time market scenario was performed in [26]. In order to maximise profits and fulfil the thermal demand of the building, an optimal operation setpoint for the next 5 minutes is determined based on the system operator real-time price signal. The decision algorithm used the relative price concept together with price sensitivity information from the end-user to set the generation system. Also, the algorithm is simple and requires low computational effort to decide the best operation point. In general, it proved to be economically feasible, in fact, it could achieve 10.3% in savings if compared to a conventional thermostat-based control strategy. Although, the authors highlighted that savings are influenced by many factors and depend on the considered scenario.

Another paper made a multi-objective optimization of a trigeneration plant based on realistic conditions, such as economical, energetic and environmental criteria [8]. To solve the optimization problem, it was used a multi-objective evolutionary algorithm, which decides the optimal sizing and operation schedule. To demonstrate the effectiveness of the proposed method, energy demand from a hospital was used under fluctuating energy prices. Accordingly, the paper concluded that the Pareto-optimal set of solutions can be used on decision-making process, as it precisely shows the impact of any trade-off and its effect on the plant performance; it also affirms that trigeneration systems can be more financially attractive, energy efficient and environmentally friendly than conventional cogeneration plants; in the last observation, it declares that financial incentives has to be made in order to support entrepreneurs to invest on an optimum size system, which has usually bigger prime movers, consequently, they are more expensive.

In [27] an evaluation of additional strategies for making cogeneration and trigeneration more attractive to potential investors was performed, either by increasing the expected financial profit or decreasing the risks of such investments. Therefore, it used a case study of a hypothetical hospital in New Jersey (USA) and explored the value of demand response, capacity markets, regulation markets, accelerated depreciation, pricing of CO_2 emissions, and net metering. For mitigation of risks of uncertainty on energy prices, it examined the effectiveness of feed-in tariffs and proposes another feed-in type. The paper first conclusion was that an absorption chiller was a cost-effective addition to the CHP project; the second verdict was that there is a significant revenue potential in the new demand response programs, as well as, in the PJM regulation market; in concern of CO_2 emissions pricing, it declares that a price on CO_2 emissions will make cogeneration and trigeneration more attractive than conventional utility supplied energy; also, accelerated depreciation is an easy and effective mechanism for improving the economics of CHP and CCHP systems; finally, it affirms that risks reduction via traditional feed-in tariff is not an effective mechanism, but a two-part feed-in tariff would eliminate energy-price risks (i.e. an annual capacity payment and energy payment that adjusts with fuel costs).

From the point of view of Brazilian studies on small and micro CHP and CCHP systems, an article identified technical and economic potential of natural gas fired cogeneration systems for malls in Rio de Janeiro [28]. However, the paper concluded that results were unfavorable within the regulatory and tariff context of 2000, which indicated the need for combined policies to provide incentives for cogeneration projects in the Brazilian commercial sector on the considered year.

A more recent study made an energetic and economic analysis of a Brazilian compact trigeneration system and compared natural gas with biogas [29]. Therefore, the studied trigeneration system consisted of an internal combustion engine using natural gas or biogas as fuel, combined with an absorption chiller and two heat exchangers. The paper concludes that the compact trigeneration system applied in tertiary sector in Brazil is a good technological option.

In [30] a comparison between centralized thermal plants and decentralized cogeneration/trigeneration systems was performed considering primary energy saving and exergy destruction. The analysis was done considering two cases, the first is suitable for applications with electricity, hot water and chilled water demand, like in hotels, malls and airports; while the second is suitable for applications with electricity, hot water, steam and chilled water demand, like in hospitals and industries. The paper concluded that both methods achieved the same results if the thermal efficiency indicator is used to compare the methods; also, the analysis revealed that trigeneration systems with the same energy input are comparable with quite different thermal efficiency centralized thermal plants; in addition, case 1 is comparable to a 53% thermal efficiency power plant and case 2 is comparable to a 77% thermal efficiency power plant.

The papers presented in this section give an overall idea of research considering cogeneration and trigeneration, and also constitute the base knowledge for this present work motivations and development.

1.2 AIMS AND OBJECTIVES

Brazil has a lack of academic research on trigeneration systems, mainly when it is related to small and micro trigeneration systems, as it was shown on the literature review. Therefore, the aim and contribution of this thesis is to make and provide a technical and economical evaluation of small and micro trigeneration systems to different buildings under distinct tariff policies, to fulfil the gap of academic knowledge on small and micro trigeneration systems in Brazil.

The objectives of this work are to optimise the sizing and monthly schedule of the trigeneration systems to each study case; evaluate the maximum net present value (NPV) considering the variation of discount rate and US Dollar conversion rate; evaluate the grid dependence index, the discounted payback, the levelized cost of energy and the primary energy ratio to the maximum NPVs; and perform analyses of the results.

1.3 RELATED PUBLICATIONS

ARTHUR GONÇALVES GIVISIEZ; BRUNO HENRIQUES DIAS; LEONARDO WILLER DE OLIVEIRA; MÁRCIO ZAMBOTI FORTES. Optimal Operation and Economical Analysis of a Trigeneration System. In: Simpósio Brasileiro de Sistemas Elétricos, 2018, Niterói. IEEE: doi:10.1109/SBSE.2018.8395741

1.4 STRUCTURE OF THE THESIS

The thesis is organised in four sections: first, section 2 presents the methodology used in this work; second, section 3 displays the case studies results and analyses; and third, section 4 has the conclusion of this work.

2. METHODOLOGY

This chapter provides the general methodology applied to evaluate the four study cases of this thesis. The algorithms were programmed in Matlab®.

The investment cost considers only the price of three important equipment: prime mover, absorption chiller and boiler. It was done so because all study cases are considered to be a retrofit project, so most of the existent infrastructure is utilised. In the light of tariffs, the electricity tariff is increased by 6% every year, and it is based on the past eight years readjustments [31,32]. In contrast with electricity tariffs, the natural gas tariffs are not readjusted on this work, because natural gas tariffs readjustment are difficult to predict in Brazil.

In regard of equipment efficiency, the proposed methodology considers fixed nominal efficiency to all equipment, as a consequence, the part-load efficiency behaviour is not considered, even when an equipment is not operating at nominal load.

The natural gas calorific value can go from 8500 kcal/m^3 to 9400 kcal/m^3 according to Goiasgás [33], so it was used an average value of 9070 kcal/m^3 in this thesis. As this work uses kWh as the custom energy measurement unit, the chosen calorific value was converted to kWh/m^3, and then the natural gas tariff was converted from R$/$m^3$ to R$/kWh.

2.1 GENERAL VIEW OF THE OPTIMISATION METHOD

The optimisation is done via one criterion, so it is done evaluations to each study case. The considered criterion is the net present value. So, this section gives the general idea of the used optimisation method.

2.1.1 Net Present Value Optimisation

The objective of this optimisation method is to find the maximum net present value to the project, considering investment and operation costs. Thus, the investment cost is considered negative and the difference between the traditional operation cost (cost of operation when the electricity is used to supply electric, heat and cold energy demands) and trigeneration operation cost is considered positive (profit), as well as, the profit is converted to present value by dividing its value by the discount rate, generally considered the minimum acceptable return rate (MARR). Thus, to have a profitable investment, the *NPV* has to be higher than zero. The general optimisation objective function is presented in (1).

$$\max NPV = -INV + \sum_{t=1}^{n} \frac{OP_{Trad_t} - OP_{CCHP_t}}{(1 + DISCOUNT\_RATE)^{\wedge t}} \quad (1)$$

where,

INV => equipment initial investment cost (R$);

OP_{Trad_t} => traditional operational cost (R$) in the year *t*;

$OP_{CCH\ t}$ => trigeneration operational cost (R$) in the year *t*;

$DISCOUNT\_RATE$ => discount rate, which represents the interest rate;

n => number of considered years.

2.1.2 Constraints Considered in the Optimisation Problem

The previously presented method has some constraints, so their general equations are presented in this section.

a) Prime mover electric efficiency:

$$GEN\_ELECTRICITY = ELE\_PMOVER\_EFFICIENCY * FUEL\_PMOVER \quad (2)$$

where,

$GEN\_ELECTRICITY$ => electric energy generated in the prime mover (kWh);

$ELE\_PMOVER\_EFFICIENCY$ => electric efficiency of the prime mover;

$FUEL\_PMOVER$ => primary energy input to the prime mover (kWh).

b) Boiler efficiency:

$$HEAT\_BOILER = BOILER\_EFFICIENCY * FUEL\_BOILER \quad (3)$$

where,

$HEAT\_BOILER$ => heat energy generated in the boiler (kWh);

$BOILER\_EFFICIENCY$ => efficiency of the boiler;

$FUEL\_BOILER$ => primary energy input to the boiler (kWh).

c) Prime mover thermal efficiency:

$$GEN\_HEAT = HEAT\_PMOVER\_EFFICIENCY * FUEL\_PMOVER \qquad (4)$$

where,

GEN_HEAT => heat energy generated in the prime mover (kWh);

$HEAT\_PMOVER\_EFFICIENCY$ => heat efficiency of the prime mover.

d) Chiller efficiency:

$$COLD\_CHILLER = COP\_CHILLER * HEAT\_CHILLER \qquad (5)$$

where,

$COLD\_CHILLER$ => cold energy generated in the chiller (kWh);

$COP\_CHILLER$ => coefficient of performance (efficiency) of the chiller;

$HEAT\_CHILLER$ => input heat energy to the chiller (kWh).

e) Electric demand fulfilment:

$$GEN\_ELECTRICITY + ELE\_GRID\_IN = ELE\_DEM \qquad (6)$$

where,

ELE_GRID_IN => imported electric energy from the grid (kWh);

ELE_DEM => electric energy demand.

f) Thermal demand fulfilment:

$$HEAT\_BOILER + GEN\_HEAT - COLD\_CHILLER = HEAT\_DEM \qquad (7)$$

where,

$HEAT\_DEM$ => heat energy demand.

g) Cold demand fulfilment:

$$COLD\_CHILLER = COLD\_DEM \tag{8}$$

where,

$COLD\_DEM$ => cold energy demand.

h) Thermal chiller constraint:

$$HEAT\_CHILLER \leq HEAT\_BOILER + GEN\_HEAT \tag{9}$$

i) Upper Bound:

$$GEN\_ELECTRICITY \leq PMOVER\_NOM\_ELE$$

$$HEAT\_BOILER \leq BOILER\_NOM$$

$$GEN\_HEAT \leq PMOVER\_NOM\_HEAT$$

$$COLD\_CHILLER \leq \infty$$

$$HEAT\_CHILLER \leq \infty$$

$$FUEL\_PMOVER \leq \infty$$

$$FUEL\_BOILER \leq \infty$$

$$ELE\_GRID\_IN \leq \infty$$

$$INVESTMENT\_COST \leq \infty$$

where,

$PMOVER\_NOM\_ELE$ => maximum rated electric energy generation capacity of the prime mover (kWh);

$BOILER\_NOM$ => maximum rated heat energy generation capacity of the boiler (kWh);

$PMOVER\_NOM\_HEAT$ => maximum rated heat energy generation capacity of the prime mover (kWh);

$INVESTMENT\_COST$ => cost of equipment investment (R$).

j) Lower Bound:

$$GEN\_ELECTRICITY \geq 0$$

$$HEAT\_BOILER \geq 0$$

$$GEN\_HEAT \geq 0$$

$$COLD\_CHILLER \geq 0$$

$$HEAT\_CHILLER \geq 0$$

$$FUEL\_PMOVER \geq 0$$

$$FUEL\_BOILER \geq 0$$

$$ELE\_GRID\_IN \geq 0$$

$$INVESTMENT\_COST \geq 0$$

It is important to clarify that the method does not mix energy with money, as it may seem to do on a first glance. Therefore, the traditional and trigeneration operation equations will be fully and detailed presented on the sequence, and the feeling of confusion will be solved.

2.2 DETAILED OPTIMISATION METHODS

2.2.1 Detailed Optimisation to Green Tariff Cases

The detailed optimisation formulas to study cases 1, 3 and 4 are presented in this section. The general equation (1), presented before, is detailed in equations (10) and (11).

The traditional operational cost per year is,

$$OP_{Trad_t} = \sum_{x=1}^{m}((ELE_{dem\_off\_peak_x} + \frac{HEAT_{dem\_off\_peak_x}}{\eta\_boiler\_ele} + \frac{COLD_{dem\_off\_peak_x}}{COP\_chiller\_ele}) * ELE_{tariff\_off\_peak_t} + ELE_{dem\_peak_x} + \frac{HEAT_{dem\_peak_x}}{\eta\_boiler\_ele} + \frac{COLD_{dem\_peak_x}}{COP\_chiller\_ele}) * ELE_{tariff\_peak_t} + \frac{COLD_{de\ \ x}}{COP\_chiller\_ele} * O\&M_{ele\_chiller\_cost} + \frac{HEAT_{de\ \ x}}{\eta\_boiler\_ele} * O\&M_{ele\_boiler\_cost} + DEM\_cost_x) \quad (10)$$

where,

$ELE_{dem\_off\_peak_x}$ => electric energy demand (kWh) at off peak time in the month x;

$HEAT_{dem\_off\_peak_x}$ => heat energy demand (kWh) at off peak time in the month x;

$COLD_{dem\_off\_peak_x}$ => cold energy demand (kWh) at off peak time in the month x;

$ELE_{tariff\_off\_peak_t}$ => electric energy tariff price (R$/kWh) at off peak time in the year t;

$ELE_{dem\_peak_x}$ => electric energy demand (kWh) at peak time in the month x;

$HEAT_{dem\_peak_x}$ => heat energy demand (kWh) at peak time in the month x;

$COLD_{dem\_peak_x}$ => cold energy demand (kWh) at peak time in the month x;

$ELE_{tariff\_peak_t}$ => electric energy tariff price (R$/kWh) at peak time in the year t;

$COLD_{dem_x}$ => total cold energy demand (kWh) in the month x;

$O\&M_{ele\_chill\quad\_cost}$ => operational and maintenance costs (R$/kWh) of the electric chiller;

$HEAT_{de\quad x}$ => total heat energy demand (kWh) in the month *x*;

$O\&M_{ele\_boiler\_cost}$ => operational and maintenance costs (R$/kWh) of the electric boiler;

DEM_cost_x => electricity demand cost (R$/kW) in the month *x*;

η_boiler_ele => electric boiler efficiency;

$COP\_chiller\_ele$ => electric chiller coefficient of performance (COP).

and the CCHP operational cost per year is,

$$OP_{CCHP_t} = \sum_{x=1}^{m}((ele_{PM\_off\_peak_x} + ele_{PM\_peak_x}) * O\&M_{PM\_cost} + heat_{boiler_x} * O\&M_{boile\quad\_cost} + ele_{grid\_in\_off\_peak_x} * ELE_{tariff\_off\_peak_t} + ele_{grid\_in\_peak_x} * ELE_{tariff\_peak_t} + cold_{chill\quad x} * O\&M_{chiller\_cost} + (f_{PM\_off\_peak_x} + f_{PM\_peak_x} + f_{boiler_x}) * FUEL_{tariff} + DEM\_cost_x + FUEL_{fix\_tariff}) \quad (11)$$

where,

$ele_{PM\_off\_peak_x}$ => electric energy generated (kWh) at off peak time by the prime mover in the month *x* (optimization decision);

$ele_{PM\_peak_x}$ => electric energy generated (kWh) at peak time by the prime mover in the month *x* (optimisation decision);

$O\&M_{PM\_cost}$ => operational and maintenance costs (R$/kWh) of the prime mover;

$heat_{boil\quad x}$ => heat energy generated (kWh) by the gas boiler in the month *x* (optimisation decision);

$O\&M_{boiler\_cost}$ => operational and maintenance costs (R$/kWh) of the gas boiler;

$ele_{grid\_in\_off\_peak_x}$ => imported electric energy (kWh) at off peak time in the month *x* (optimization decision);

$ELE_{tariff\_off\_peak_t}$ => electric energy tariff price (R$/kWh) at off peak time in the year *t*;

$ele_{grid\_in\_peak_x}$ => imported electric energy (kWh) at peak time in the month *x* (optimization decision);

$ELE_{tariff\_peak_t}$ => electric energy tariff price (R$/kWh) at peak time in the year *t*;

$FUEL_{tariff}$ => natural gas tariff (R$/kWh);

$cold_{chill\quad x}$ => cold energy generated (kWh) by the chiller in the month *x* (optimisation decision);

$O\&M_{chiller\_cost}$ => operational and maintenance costs (R$/kWh) of the chiller;

$f_{PM\_off\_peak_x}$ => natural gas primary energy input (kWh) at off peak time to the prime mover in the month x (optimisation decision);

$f_{PM\_peak_x}$ => natural gas primary energy input (kWh) at peak time to the prime mover in the month *x* (optimisation decision);

f_{boiler_x} => natural gas primary energy input (kWh) to the gas boiler in the month *x* (optimisation decision);

DEM_cost_x => electricity demand cost (R$/kW) in the month *x*;

$FUEL_{fix\_tariff}$ => fixed natural gas tariff.

As presented in this section, the tariff system to study cases 1, 3 and 4 have two parts, the first part charges the contracted demand, while the second one charges consumed electric energy over the month. Also, the consumed electric energy tariff is time-of-use based, then it has a peak tariff and an off-peak tariff.

2.2.2 Detailed Optimisation to Custom Residential Tariff Case

The detailed optimisation formulas to study case 2 are presented in this section. They are quite similar to the other cases, but some differences are present because of a distinct policy is used in the case 2. Again, the general equation (1), presented before, is detailed in equations (12) and (13).

The traditional operational cost per year is,

$$OP_{Trad_t} = \sum_{x=1}^{m} ((ELE_{dem_x} + \frac{HEAT_{dem_x}}{\eta\_boiler\_ele} + \frac{COLD_{dem_x}}{COP\_chiller\_ele}) * ELE_{tariff_t} + \frac{COLD_{dem_x}}{COP\_chiller\_ele} * O\&M_{ele\_chiller\_cost} + \frac{HEAT_{dem_x}}{\eta\_boiler\_ele} * O\&M_{ele\_boiler\_cost}) \quad (12)$$

where,

ELE_{dem_x} => electric energy demand (kWh) in the month *x*;

$HEAT_{dem_x}$ => heat energy demand (kWh) in the month *x*;

$COLD_{dem_x}$ => cold energy demand (kWh) in the month *x*;

ELE_{tariff_t} => electric energy tariff price (R$/kWh) in the year *t*;

and the CCHP operational cost per year is,

$$OP_{CCHP_t} = \sum_{x=1}^{m} (ele_{PM_x} * O\&M_{PM\_cost} + heat_{boiler_x} * O\&M_{boiler\_cost} + ele_{grid\_in_x} * ELE_{tariff_t} + cold_{chiller_x} * O\&M_{chill\_cost} + (f_{PM_x} + f_{boiler_x}) * FUEL_{tariff} + FUEL_{fix\_tariff}) \quad (13)$$

where,

ele_{PM_x} => electric energy generated (kWh) by the prime mover in the month *x* (optimization decision);

$heat_{boiler_x}$ => heat energy generated (kWh) by the gas boiler in the month *x* (optimisation decision);

$ele_{grid\_in_x}$ => imported electric energy (kWh) in the month *x* (optimization decision);

f_{PM_x} => natural gas primary energy input (kWh) to the prime mover in the month x (optimisation decision);

As presented in this section, the tariff system to study case 2 is simpler than the other study cases. This happens because study case two works with a custom residential tariff system, which does not charge contracted demand and has only one electric energy tariff to the entire day.

2.3 EVALUATION PARAMETERS

The results from the optimisation, the net present value, together with discounted payback, grid dependence index, primary energy ratio and levelized cost of energy are used as evaluation criteria in the present study.

Among those criteria, the NPV and discounted payback are financial parameters, so it can help investors to have an overview of possible economic benefits. Equally important is the levelized cost of energy, which gives a relation between the total cost and the total produced energy. The formula of discounted payback is presented in (14).

$$INV = \sum_{time=}^{n} \frac{CASH\_FLOW_t}{(1 + DISCOUNT\_RATE)^{\wedge time}} \tag{14}$$

where,

$CASH\_FLOW$ => cash flow of the project.

$time$ => payback time (years);

The formula of the levelized cost of energy (R$/kWh) is presented in (15).

$$LCOE = \frac{INV + \sum_{t=1}^{n} \frac{OP_{CCHP_t}}{(1 + DISCOUNT\_RATE)^{\wedge t}}}{\sum_{t=1}^{n} \frac{TOTAL\_PRODUCED\_ENERGY_t}{(1 + DISCOUNT\_RATE)^{\wedge t}}} \tag{15}$$

where,

$TOTAL\_PRODUCED\_ENERGY_t$ => total produced energy in the year t.

In the light of network dependence, the grid dependence index, (16), shows how much the building energy system depends on the external power network.

$$GDI(\%) = \frac{CCHP\_GRID\_DEPENDENCE}{TRAD\_GRID\_DEPENDENCE} * 100 \qquad (16)$$

where,

$CCHP\_GRID\_DEPENDENCE$ => grid dependence when using the trigeneration system;

$TRAD\_GRID\_DEPENDENCE$ => grid dependence when using the traditional system.

From the energetic point of view, the primary energy ratio gives a system efficiency of primary energy conversion to final useful energy [34], as in (17).

$$PER = \frac{FINAL\_USEFUL\_ENERGY}{INPUT\_FUEL\_ENERGY} \qquad (17)$$

where,

$FINAL\_USEFUL\_ENERGY = HEAT\_BOILER + GEN\_HEAT - HEAT\_CHILLER + COLD\_CHILLER + GEN\_ELECTRICITY$;

$INPUT\_FUEL\_ENERGY = FUEL\_BOILER + FUEL\_PMOVER$.

2.4 DETAILED OPTIMISATION PROCESS

The detailed optimisation processes to the four study cases are presented in this section. However, there are general variables that change according to the studied case, so they will be set on their respective study case section. The detailed flowchart of the processes is presented in Figure 4.

The first step is the input of all necessary data to the simulation, such as energy demand in kW (i.e. electricity, cold and heat demands), equipment efficiency (i.e. prime mover, natural gas boiler, absorption chiller, old electric boiler and old electric chiller efficiencies), energy related tariffs in R$/kWh or R$/kW (i.e. electric energy, electric demand, natural gas and fixed natural gas tariffs), equipment O&M costs in US$/kWh (i.e. prime mover, natural gas boiler, absorption chiller, old electric boiler and old electric chiller O&M costs) and new equipment prices in US$ (i.e. prime mover, natural gas boiler and absorption chiller prices).

Then, in step 2, the equipment price extrapolation is done to generate reference prices (US$/kW) for the calculation of equipment initial investment. To do so, the input equipment prices of each machine are used as base to a linear extrapolation process.

In the sequence, in step 3, the annual electricity readjustment, 6% per year, is calculated to each of the 15 years considered in this work. After, the discount rate (*discount_rate*) and US Dollar conversion rate (*dollar*) are set at its initial value, 0% and R$3.00 respectively.

In step 4, the input O&M cost (US$/kWh) to each equipment is converted to R$/kWh based on the updated US Dollar conversion rate.

In the sequence, in step 5, the traditional operational cost in Brazilian Real is calculated for the 15 years with the use of equation (10) for the cases of green tariff, and using equation (12) in the case of custom residential tariff. Then, the prime mover (*Cpm*) and boiler (*boiler*) initial sizing are set as zero in each one.

Next, in step 6, there is the calculation of the prime mover and the boiler investment costs to the corresponding updated sizes. They are based on the previously calculated equipment reference prices. Also, the equipment investment cost is converted to Brazilian Real according to the updated US Dollar conversion rate.

In step 7, the operation cost optimisation of the trigeneration system is performed. To do so, equation (11) and the initial investment cost of the prime mover and the boiler are used in the green tariff cases, while in the custom residential tariff case it is used equation (13) and also the initial investment cost of the prime mover and the boiler. At this step all the necessary values to the optimisation are in Brazilian Real. Additionally, linear programming is used to solve the problem.

Therefore, in step 8, there is the addition of the chiller investment cost in Brazilian Real, also based on the updated US Dollar conversion rate and reference equipment prices, to the other investment cost. In the sequence, the maximization of the NPV in Brazilian Real, described in equation (1), is concluded to the current situation of discount rate and US Dollar conversion rate.

Then, the boiler heat capacity is increased by a specific value (*dcboiler*) in step 9, and it returns to step 6 until the maximum boiler capacity (*mboiler*) is achieved.

When the maximum boiler capacity (*mboiler*) is achieved, the algorithm goes to step 10. This step increases the prime mover electric capacity by a specific value (*dCpm*), and then the boiler capacity is reinitiated and the algorithm is redirected to step 6. This action is performed until the maximum prime mover electric capacity (*mCpm*) is achieved.

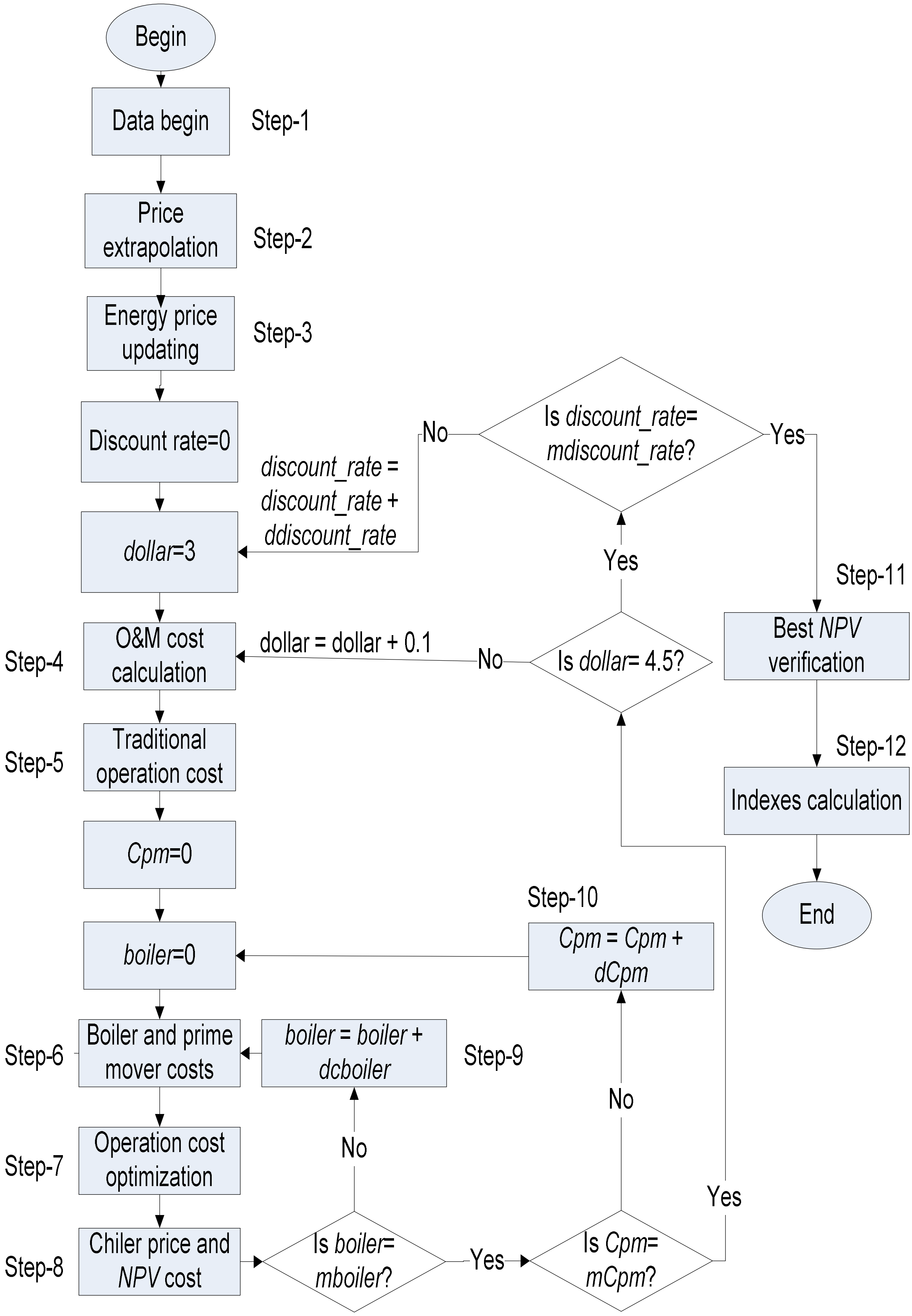
Therefore, the algorithm goes to the *dollar* increase step. This part sums the previous US Dollar conversion rate (*dollar*) with US$ 0.1, and then the algorithm goes back to step 4. This action is performed until the US Dollar conversion rate achieves US$ 4.5.

Thus, the algorithm moves to the *discount_rate* increase step. This part sums the previous discount rate (*discount_rate*) by a specific value (*ddiscount_rate*), and then the *dollar* is reinitiated and the algorithm is redirected to step 4. This action is performed until the maximum discount rate (*mdiscount_rate*) is achieved.

In the sequence, in step 11, the verification of the best NPV in Brazilian Real to each US Dollar conversion rate and discount rate situation is performed.

Finally, in step 12, there are the calculation of grid dependence index, the discounted payback, the levelized cost of energy, and the primary energy ratio to the best NPVs. The same procedure is done with and without equipment's taxes at the time of purchase.

Figure 4 – Methodology flowchart to the study cases



Source: Author

3. CASE STUDIES AND RESULTS

As previously mentioned, the most important contribution of this work is the application and evaluation of trigeneration systems in typical Brazilian buildings, considering local tariff prices and policies. So, this chapter presents details of the four case studies and their respective reference cases, as well as, their results are disclosed and analysed.

3.1 SELECTION OF EQUIPMENT AND INITIAL INVESTMENT

All the four trigeneration cases use similar equipment, the only parameter that changes is the sizing of the apparatus. Thus, it is presented the main characteristics of the machinery at once. Also, reference cases' equipment are displayed in this section.

The first observation is that a reciprocating engine was selected as the prime mover, as well as, natural gas was the chosen fuel. This prime mover alternative was chosen because of its sizing range and price, as we needed a small size and financially competitive prime mover. The fuel alternative was related to its price and low associated pollution, if compared to others fossil fuels. A possible alternative to natural gas could be the biogas, but the offer of such fuel is lower than the natural gas offer. Additionally, the reciprocating engine initial investment value (US$/kW) are taken from [35], which includes engine, generator, construction and installation prices. Then, the five prices from the document were used as base to a linear extrapolation, which becomes the initial investment cost reference to the prime mover.

The second consideration is about thermal energy equipment, the chosen option for cooling was an absorption chiller that uses hot water as a heat source. In like manner, there is the need of an auxiliary boiler to supply the share of hot water that the prime mover cannot provide. The chosen one was a natural gas boiler, to take advantage of the natural gas supply already used in the prime mover, also because natural gas tariffs are cheaper than electricity. Moreover, the absorption chiller initial investment value (US$/kW) and natural gas boiler initial investment value (€/kW) are taken from [36] and [37], respectively. Then, the prices from the two documents were used as a base to a linear extrapolation, each one with its own price, which becomes initial investment cost references to the absorption chiller and natural gas boiler. Also, the Euro investment value is converted to US Dollar with a conversion rate of €1.0 to US$1.17, which is from May, 2018.

The third, and last observation, is related to the reference cases. As reference cases are electricity-based systems, the main source of energy considered was the external network. As a consequence, it was used an electric boiler to heat supply and an electric chiller to fulfil the cooling demand. In this work, the electric machinery is considered old, because it is a retrofit project, so its efficiency may be slightly lower than current efficiency to same equipment.

The main considered parameters to equipment are presented in Table 1, and they are used in the four study cases.

Table 1 – Equipment efficiency and O&M cost

Equipment	Efficiency/COP	O&M cost (US$/kWh)	References
Reciprocating engine - Electric	0.296	0.024	[35]
Reciprocating engine - Heat	0.532		[35]
Auxiliary boiler	0.85	0.003242	[38,8]
Absorption chiller (COP)	0.72	0.001136	[36]
Old electric boiler	0.819	0.000585	[39,40]
Old electric chiller (COP)	3	0.001623	[41]

Source: Various sources (indicated in the table)

3.2 CASE STUDY 1

The first discussed case is a hospital hypothetically located in Minas Gerais State, and connected to the medium voltage network. The electrical tariff policy used by the hospital is named A4 green tariff, which has one fixed demand tariff and the electric energy tariff is time-of-use based [42]. Moreover, all the tariffs are already with taxes (ICMS[4], PASEP[5] and COFINS[6]) and it was used the green flag value, in other words, when there is no additional charge in the energy fee due to bad hydrological condition. The demand and electric energy tariffs with taxes, and the applied taxes percentage used on this work are presented in Table 2 (they are from June, 2018) [32,43].

[4] According to Secretaria do Estado da Fazenda of Minas Gerais the ICMS is defined as a non-cumulative tax charged on operations related to the movement of goods and services of interstate and inter-municipal transportation and communication services. It is competence of the States and the Federal District, as provided in art. 155, II, of the 1988 Constitution, it is one of the main sources of financial resources for the achievement of governmental actions [47].

[5] According to Tesouro Nacional the original objectives of PASEP (federal contribution) are to integrate the employee into the life and development of enterprises, to ensure the employee and the public servant the usufruct of progressive individual assets, to stimulate savings and to correct distortions in the distribution of income and to enable parallel use of resources accumulated in favor of socio-economic development [48].

[6] According to the Brazilian Government COFINS is a federal contribution that focuses on the monthly turnover of companies [49].

Table 2 – Demand and electricity tariffs, and taxes percentage to study case 1

Taxes names	ICMS	PASEP	COFINS
Taxes (%)	18	0.56	1.90
Time of use periods	**From 0h to 18h**	**From 18h to 21h**	**From 21h to 0h**
Electricity tariff price – first year (R$/kWh)	0.4059	1.9403	0.4059
Demand price (R$/kW)	18.3430	18.3430	18.3430

Source: Companhia Energética de Minas Gerais - CEMIG, 2018

The natural gas tariff used by the hospital is named cogeneration tariff, which has a fixed and a variable tariff. Moreover, all the tariffs are already with taxes (ICMS, PASEP and COFINS) and the variable tariff was converted to R$/kWh, as already explained. The fixed and variable natural gas tariffs with taxes, and the applied taxes percentage used on this work are presented in Table 3 (they are from June, 2018) [44].

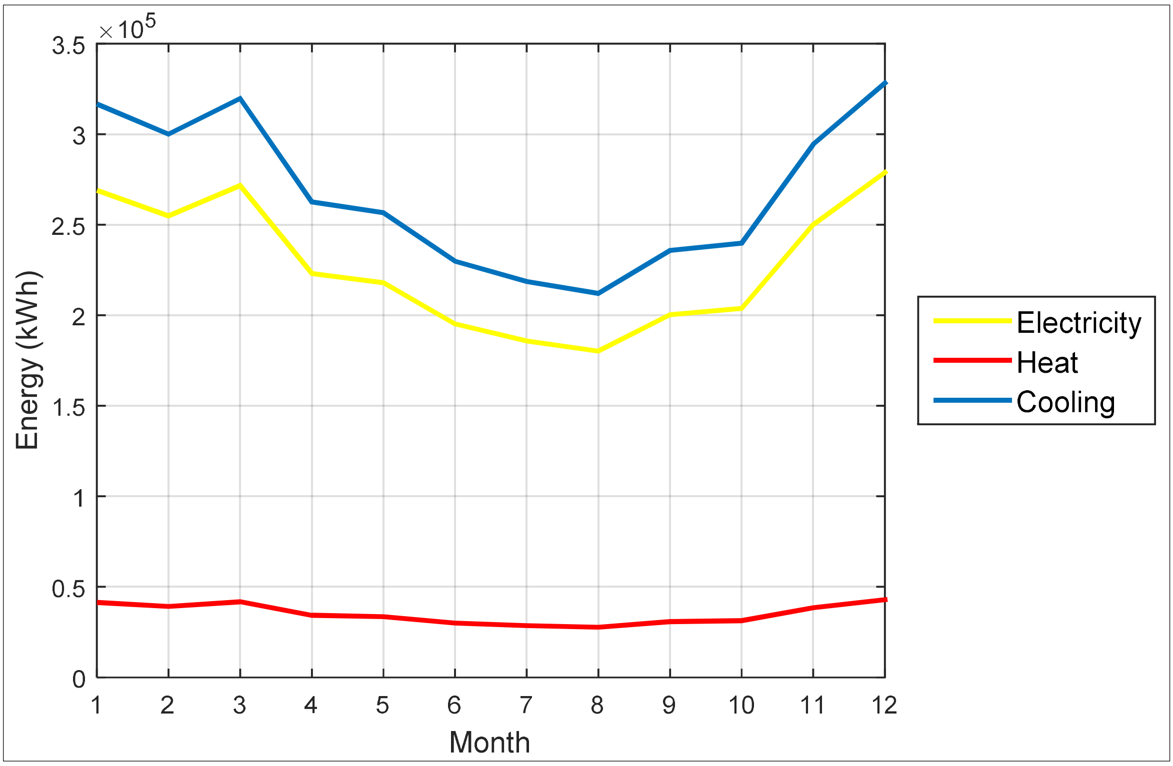
Table 3 – Fixed and variable natural gas tariffs, and taxes percentage to study case 1

Taxes names	ICMS	PASEP	COFINS
Taxes (%)	12	1.65	7.60
Tariffs		**Value**	
Natural gas tariff (R$/kWh)		0.1731	
Fixed natural gas tariff (R$)		434.16	

Source: Companhia de Gás de Minas Gerais - GASMIG, 2018

Moreover, the energy demand data is from a Brazilian hospital [45]. The data was processed to match the input format used in this thesis. The processed energy demand is shown in Figure 5. Although it is not from Minas Gerais, it still represents the Brazilian weather and consumption characteristics. This is also the reason of calling the hospital as having a hypothetical location, because it is based on real data from Brazil but it is not from the same location where it was placed in this study case.

Figure 5 – Energy demand at the studied hospital



Source: Author

3.2.1 The Reference Case to the Study Case 1

As the reference case is electricity-based, the three energy demands (electricity, heating and cooling) of the hospital are summed into one electric load, always considering electric boiler and electric chiller efficiencies. Then, the electric energy tariff is applied over the consumed energy in each month, and the demand tariff is applied to the maximum demand of each month. It is important to clarify that green tariff prices to hospitals are applied (Table 2), and also it is considered an annual readjustment on the electric energy tariff. The simulation is done according to the flowchart presented in Figure 4 and some particular values to the case, which are presented in the next section.

3.2.2 Optimisation Process to Study Case 1

The first consideration about this case is that the considered lifespan of the system is 15 years, so to each simulation the number of calculated years will be limited to this value. Moreover, the discount rate (*discount_rate*) is varied from 0% to 30% in 2% steps, as well as, the US Dollar (US$) to Brazilian Real (R$) conversion price (*dollar*) is varied from R$3.00 to R$4.50 in R$0.10 steps. This sensitivity analysis is important because of the nature of these two parameters, as they modify with changes in national/international policies and economy. Equally important is the variation of the prime mover electric generation capacity (*Cpm*), from 0kW to 500kW in 50kW steps, and the boiler heat generation capacity (*boiler*), from 0kW to 800kW in 100kW steps. This action is necessary to correctly size the equipment, which can make a considerable difference on the financial return.

Considering the given information about study case 1, it is possible to set the variables present on the flowchart explained in Figure 4. So, Table 4 shows the optimization flowchart variable values to study case 1.

Table 4 – Optimization flowchart variable values to study case 1

Variable	Value
ddiscount_rate	2%
mdiscount_rate	30%
dCpm	50 kW
mCpm	500 kW
dcboiler	100 kW
mboiler	800 kW

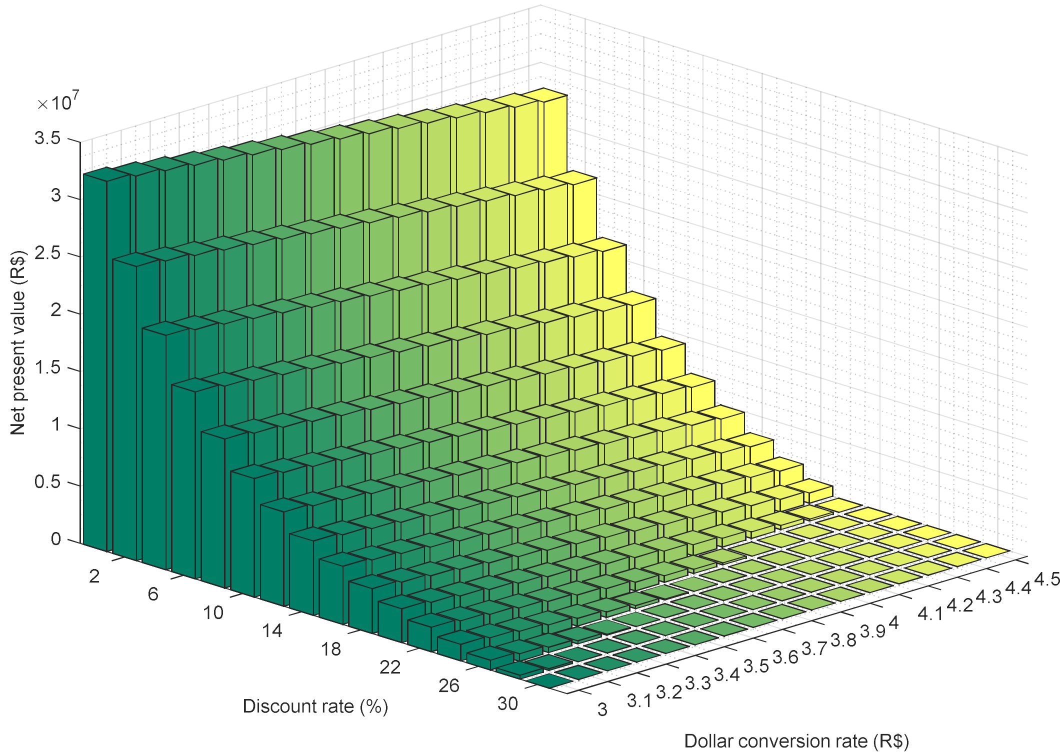
Source: Author

3.2.3 Results and Analysis to Study Case 1

This section will present simulation and analyse results from the case 1. In the first place, it will be presented the net present value sensitivity study, and then, the equivalent equipment sizing, the investment cost, the grid dependence index, the discounted payback time, the levelized cost of energy and the primary energy ratio. All of them are presented, firstly, without equipment taxes, and after, considering equipment taxes.

The first result to be presented and analysed is the net present value sensitivity study without equipment taxes. As it can be seen in Figure 6, the net present value decreases as the discount rate and dollar conversion rate increase. Also, the impact of rate variation on the NPV is higher with discount rate than with dollar. In general, the NPV is higher than zero from 0% to 18% of discount rate and to any considered US Dollar conversion rate, so this is the safest region to investment as the dollar variation does not strongly affect the investment return. However, from 20% to 28% discount rate, the positive NPV depends on the US Dollar conversion rate, therefore this region is riskier than the previous one. Otherwise, discount rate of 30% gives no financial benefit on the investment.

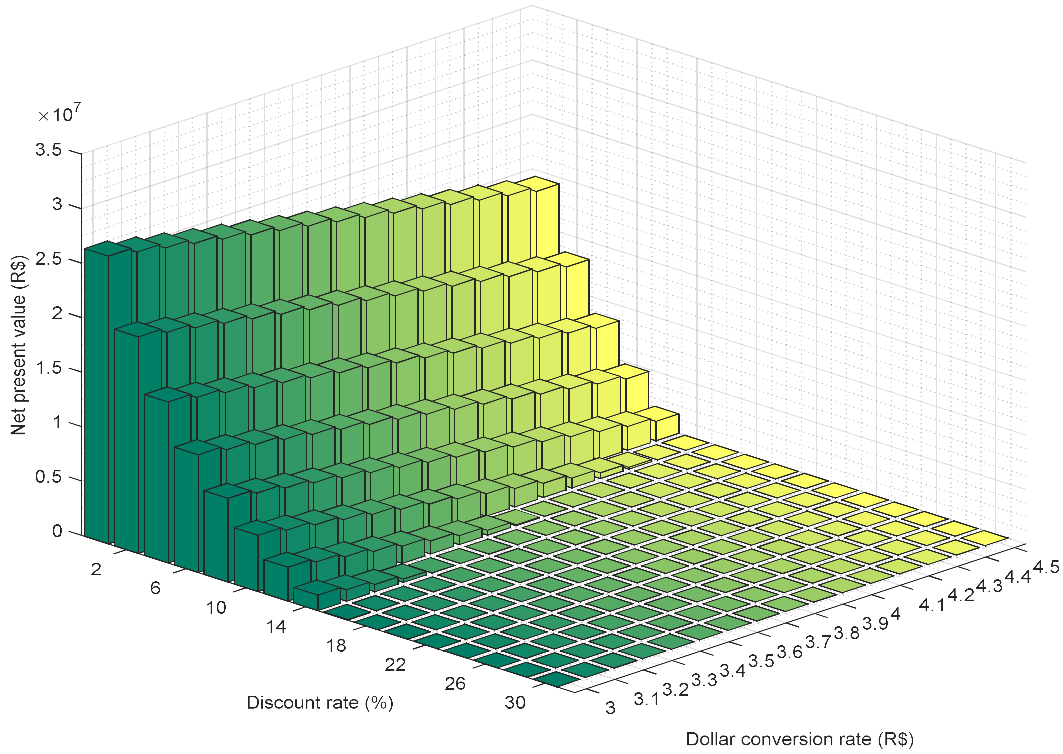
Figure 6 – Maximum net present values to the hospital case study without equipment taxes



Source: Author

The second result to be presented and analysed is the net present value sensitivity study with equipment taxes. As it can be seen on Figure 7, the net present value also decreases as the discount rate and dollar conversion rate increase, as expected. Moreover, the impact of rate variation on the NPV is also higher with discount rate than with dollar. In general, the NPV is higher than zero from 0% to 8% of discount rate and to any considered US Dollar conversion rate variation, so this is the safest region to investment. However, from 10% to 16% of discount rate, the positive NPV depends on the US Dollar conversion rate, therefore this region is riskier than the previous one. Otherwise, discount rates from 18% to 30% give no financial benefit on the investment.

Figure 7 – Maximum net present values to the hospital case study with equipment taxes

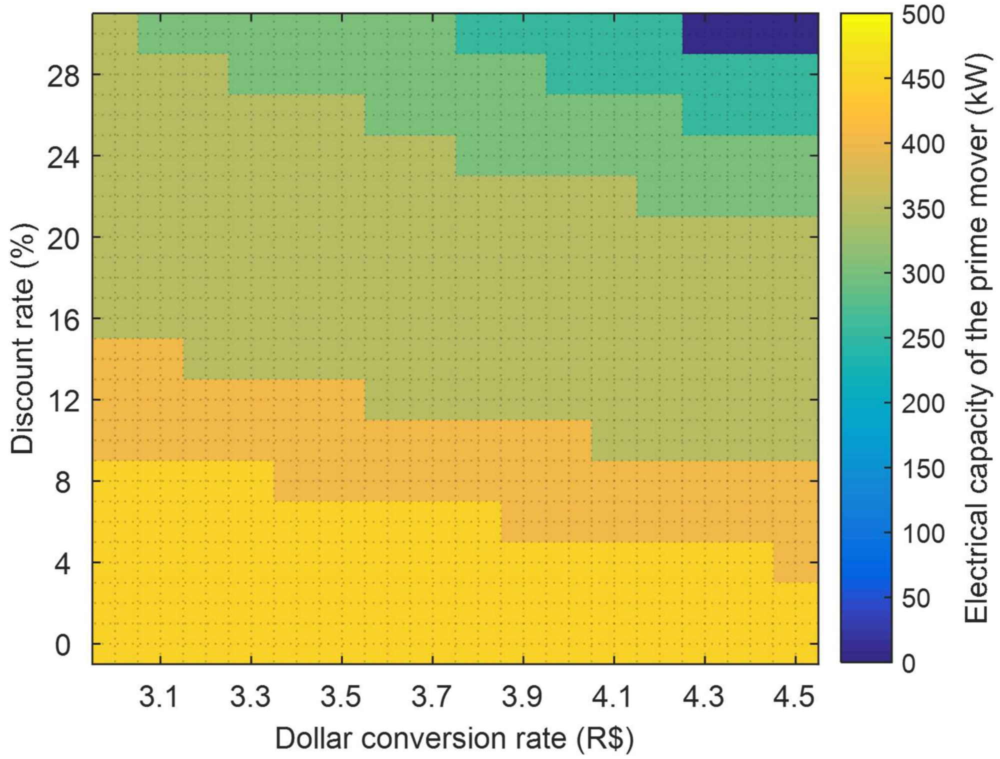


Source: Author

When Comparing the previous net present values sensitivity studies, the greatest difference is on the machinery investment price. In the first situation, the taxes imposed by the Brazilian government are ignored, consequently, the NPV is higher than in the second situation, which considers maximum estimated taxes (100%). This tax value is considered as the worst case, and it was selected as this high due to the fact that there may be differences on taxes according to different states. Therefore, from the previous situations, it can be concluded that Brazilian taxes limit the investment return on trigeneration systems.

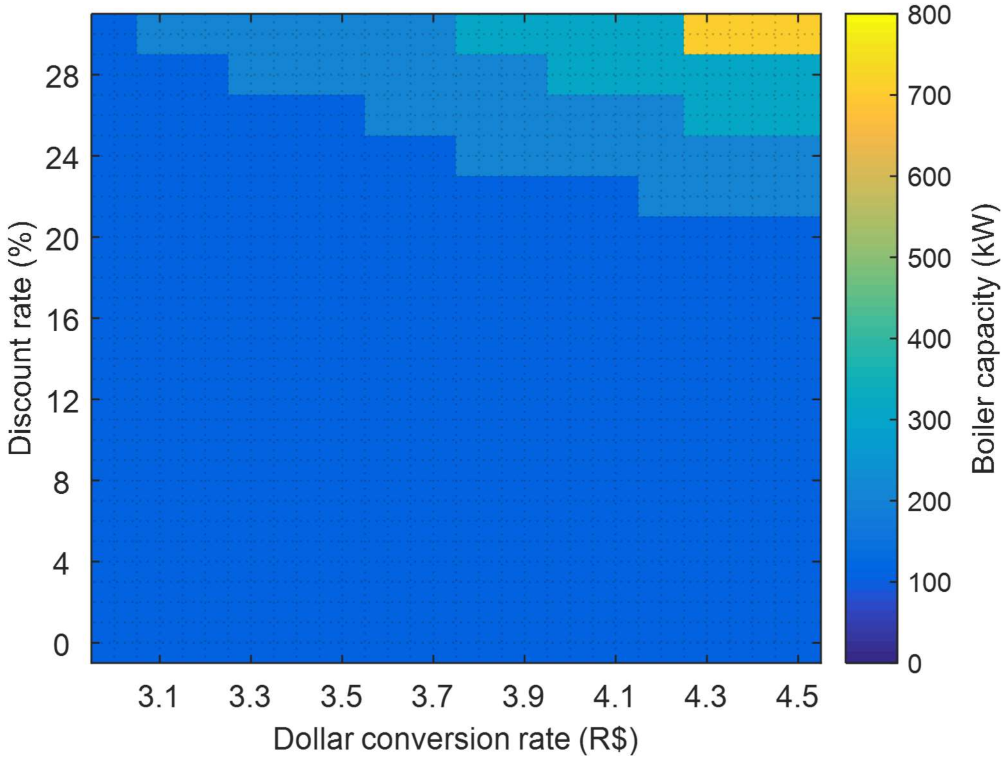
After the decision of the highest available NPVs, it is possible to find specific size to the three components of the trigeneration system, the investment cost, the grid dependence index, the discounted payback time, the levelized cost of energy, and the primary energy ratio related to the maximum NPVs. Therefore, the prime mover sizing (electrical) and boiler sizing to the hospital case without equipment taxes are presented in Figure 8 and Figure 9, respectively. Also, the absorption chiller size corresponds to the maximum cooling demand of the building. So, there is no optimal sizing study to absorption chillers on this work.

Figure 8 – Sizing of the prime mover (electrical) at maximum net present values to the hospital case without equipment taxes



Source: Author

Figure 9 – Sizing of the boiler at maximum net present values to the hospital case without equipment taxes



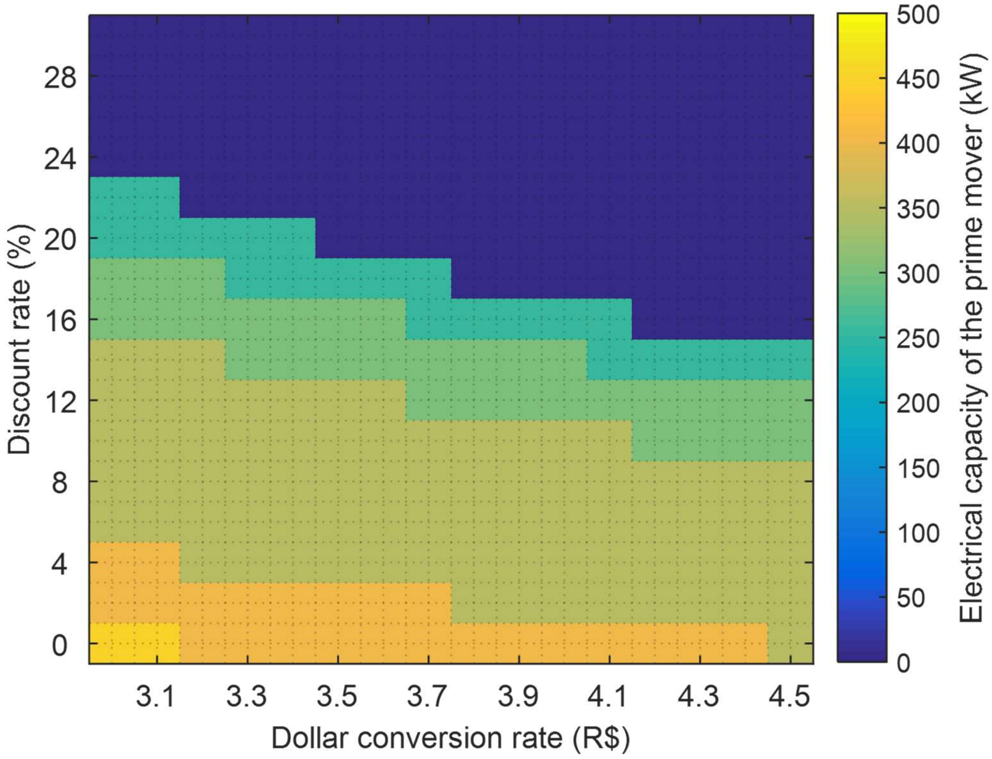
Source: Author

In general, prime mover capacity decreases as the discount rate and US Dollar conversion rate increases, thus, the prime mover size can go from 0kW to 450kW. In contrast, the boiler size capacity increases as the discount rate and US Dollar conversion rate increases, and its capacity can range from 100kW to 700kW.

If a comparison is made between the prime mover and boiler sizing capacities, it is possible to conclude that the prime mover size is complementary to the boiler size. In other words, when the prime mover is at its higher capacity, the boiler is at its lower capacity and vice versa. This happens due to the necessity of fulfilment on the heat and cold demand.

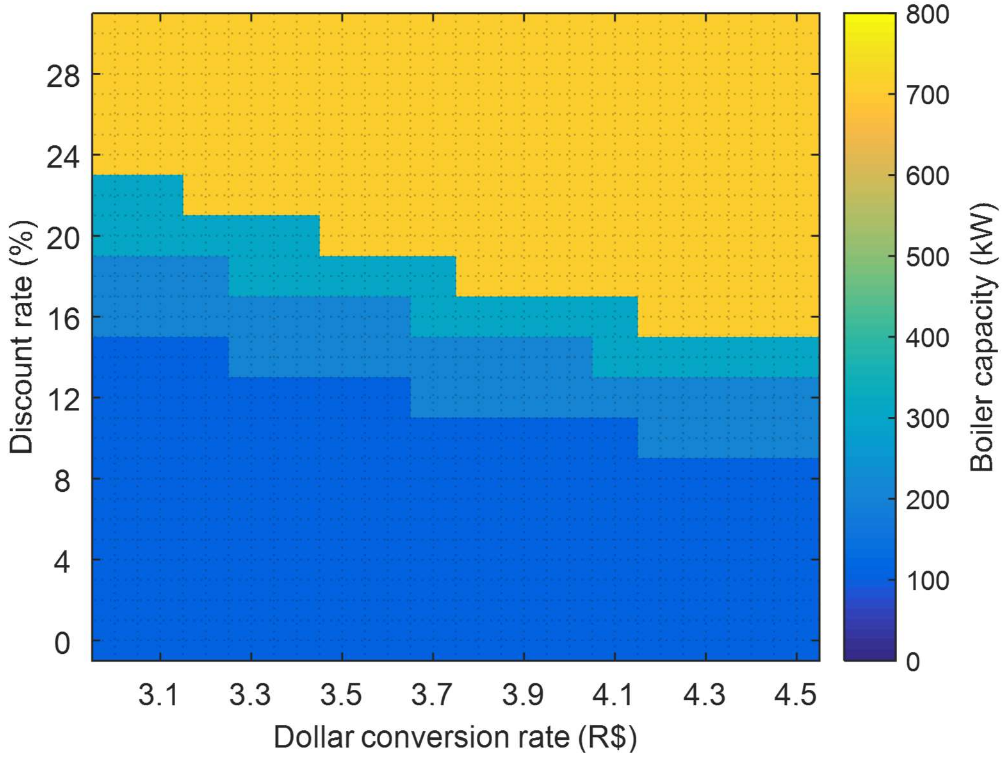
In the sequence, the prime mover sizing (electrical) and boiler sizing to the hospital case with equipment taxes are presented in Figure 10 and Figure 11, respectively. The same behaviour observed on the prime mover and boiler sizing without equipment taxes is noted this time. The only difference is that, now, the decision of no investment on trigeneration systems is a reality in more situations.

Figure 10 – Sizing of the prime mover (electrical) at maximum net present values to the hospital case with equipment taxes



Source: Author

Figure 11 – Sizing of the boiler at maximum net present values to the hospital case with equipment taxes

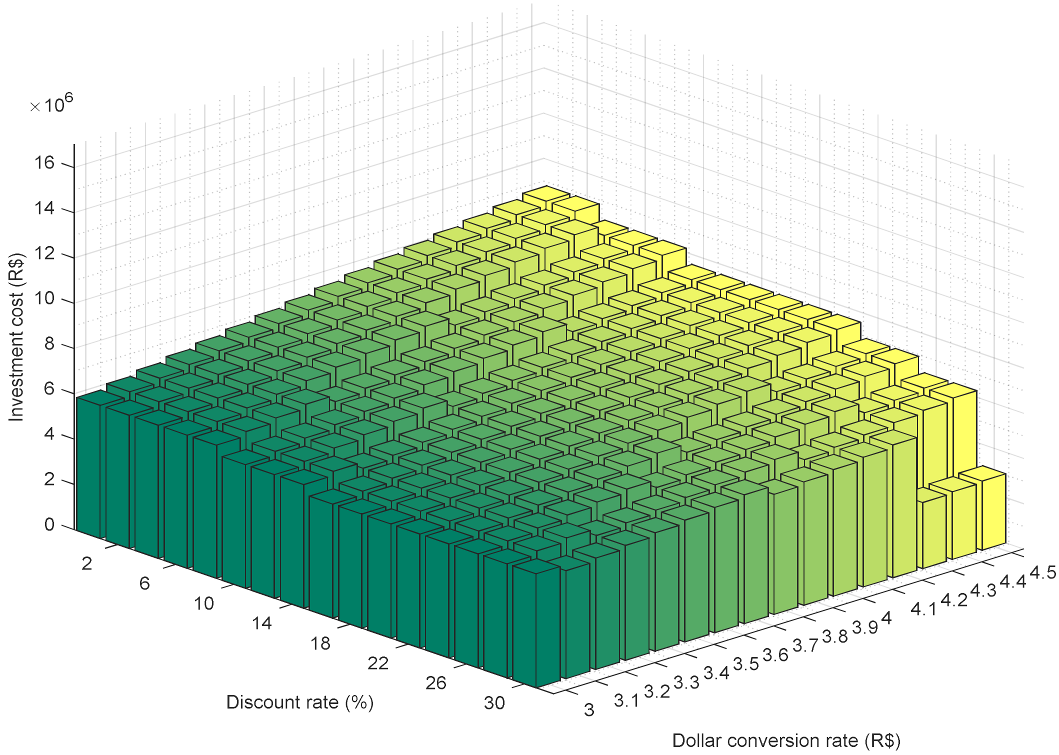


Source: Author

From the prime mover and boiler sizing, together with the absorption chiller size, it is possible to obtain the equipment investment cost. So, it is shown in Figure 12 the investment cost without taxes and in Figure 13 the same cost considering taxes. The average investment cost without taxes is around R$ 6.5 million, while the taxes rise the average investment cost to around R$ 9.5 million.

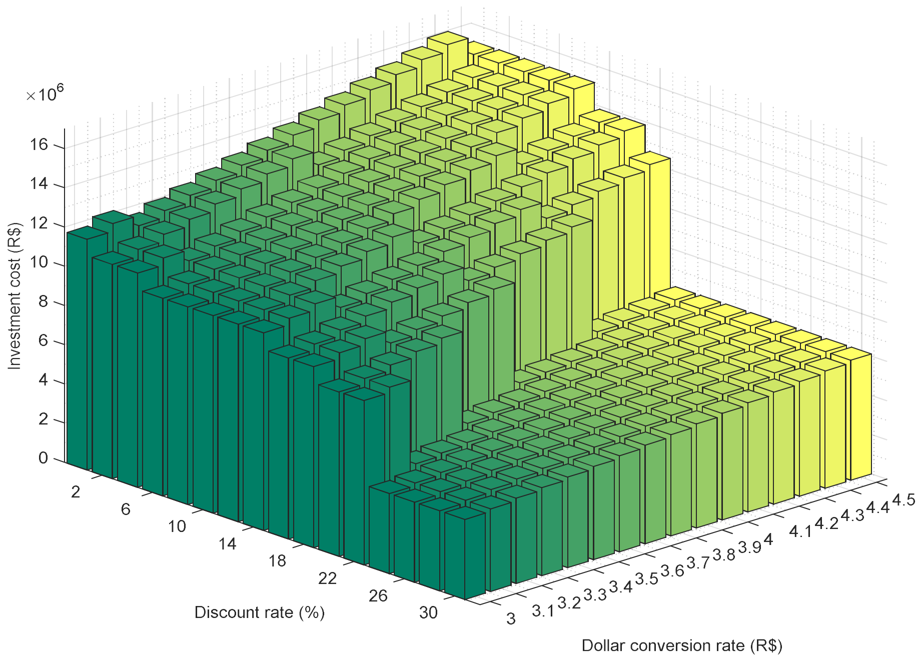
In concern of grid dependence index, Figure 14 shows its result at maximum net present values without equipment taxes. In general, the GDI is very low, almost 99% of situations are below 14% of dependence from the external grid. However, when the discount rate achieves the highest considered value and the US Dollar conversion rate is equal or higher than R$4.3, the GDI gets at its maximum value, around 63%. As can be seen in this simulation, the optimisation indicates that the trigeneration system should work with minimum power from the external network.

Figure 12 – Variation of investment cost at maximum net present values to the hospital case study without equipment taxes



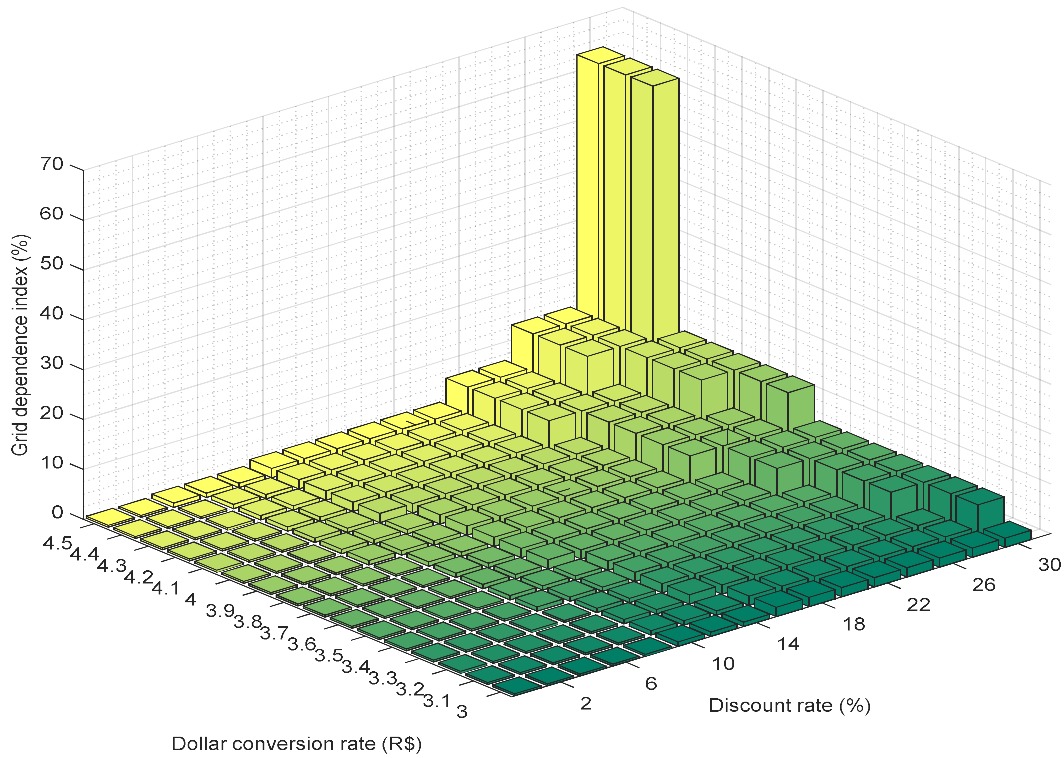
Source: Author

Figure 13 – Variation of investment cost at maximum net present values to the hospital case study with equipment taxes



Source: Author

Figure 14 – Variation on grid dependence index at maximum net present values to the hospital case without equipment taxes

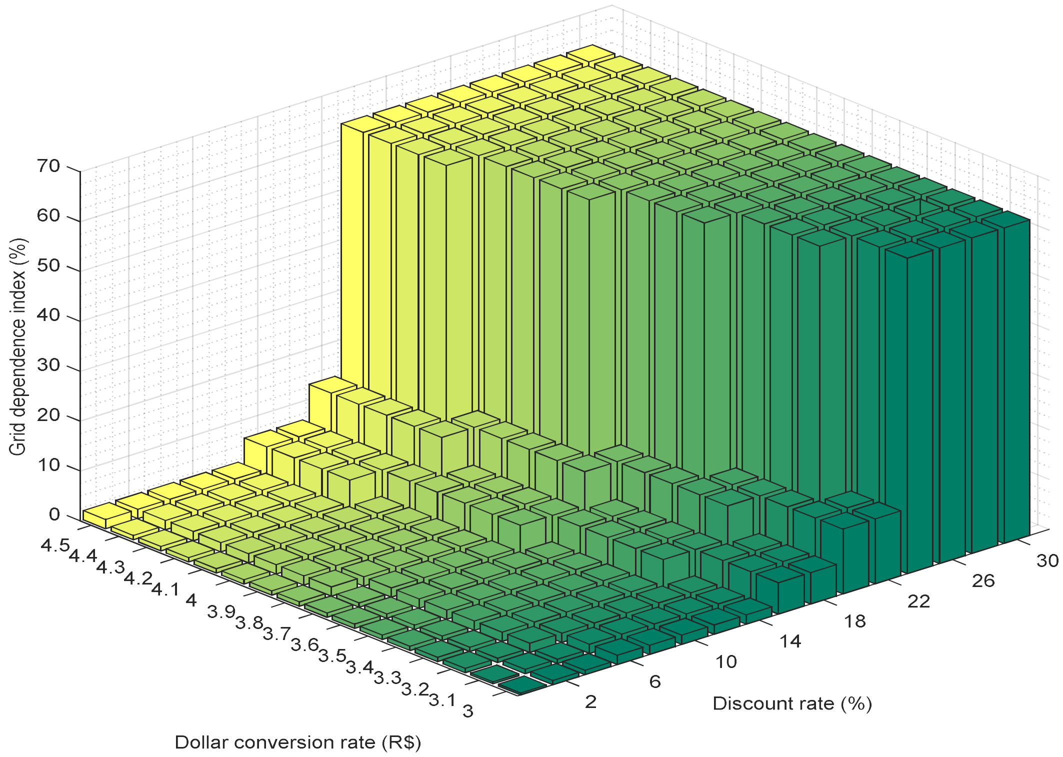


Source: Author

After, Figure 15 shows the result of grid dependence index for the building at maximum net present values with equipment taxes. At this time, the GDI is still very low to around 60% of situations, which are below 14%. However, as the discount rate gets higher, the GDI goes to its maximum values, around 63%. When the GDI achieves 63%, it means that the prime mover sizing is zero, in other words, the optimisation process decides for non-installation of a trigeneration system. As a consequence, only the boiler and absorption chiller are installed.

Analysing and comparing the two GDIs sensitivity studies, it is possible to observe that in the simulation without taxes the grid dependence is low in almost all economic situation, so the CCHP system is responsible for supplying most of the energy load. In the simulation considering taxes, although, the trigeneration system sizing and operation depend on the economic scenario, and in some cases the trigeneration system is not profitable, then, the grid dependence increases.

Figure 15 – Variation on grid dependence index at maximum net present values to the hospital case with equipment taxes



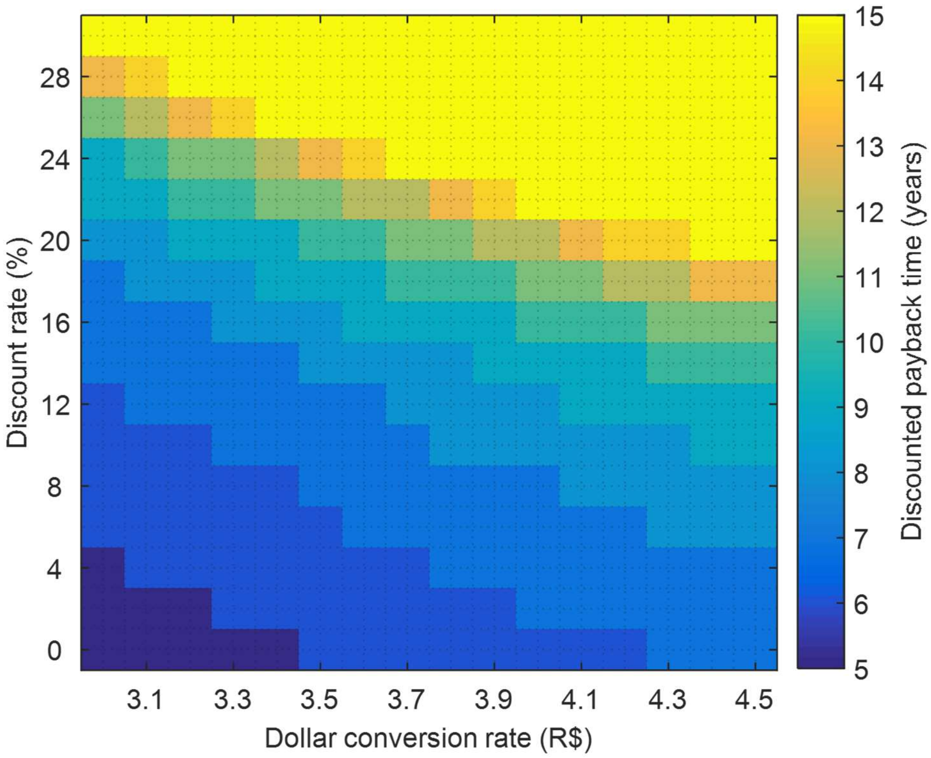
Source: Author

The next presented result is the discounted payback time without equipment taxes, Figure 16. As it can be seen, the minimum discounted payback time is 5 years, which is a fair result, but the respective discount rate is too low to a business. It is important to clarify that results represented as 15 years of payback, in this study, can be higher or equal to 15 years. Anyway, those results are not interesting to investors. In the middle, there are payback times from 6 to 10 years, which could attract the attention of a few investors who are concerned about the service quality of the distribution company network, the external grid.

Figure 17 shows the discounted payback time with equipment taxes. In this case, most of the situations are not financially beneficial, as great number of situations have discounted payback time higher than ten years. Just few situations have payback time between 8 to 10 years, but those are with low discount rate, which probably will not attract investors attention.

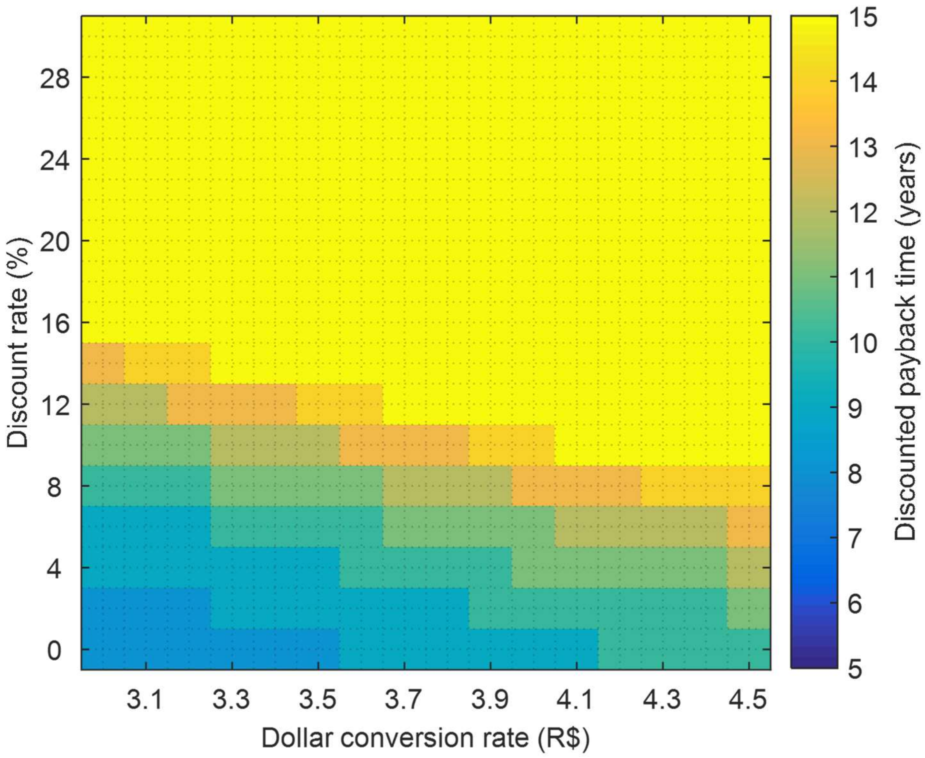
The comparison between discounted payback considering and not considering taxes reinforce that Brazilian taxes are a barrier to trigeneration systems adoption, moving the investment from a profitable scenario to a non-profitable one.

Figure 16 – Variation on discounted payback at maximum net present values to the hospital case without equipment taxes



Source: Author

Figure 17 – Variation on discounted payback at maximum net present values to the hospital case with equipment taxes

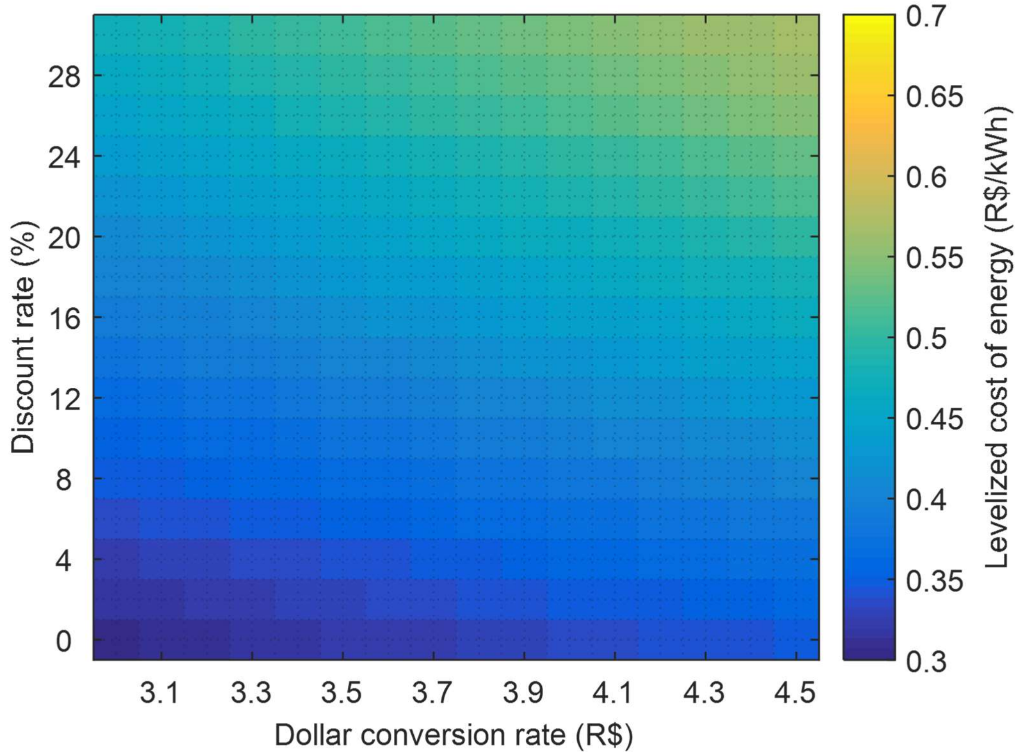


Source: Author

The levelized cost of energy to the best NPVs without equipment taxes is shown in Figure 18, while in Figure 19 there is the same result considering taxes. While in the first one the LCOE ranges from around 0.30 R$/kWh to approximately 0.56 R$/kWh, in the second one the LCOE ranges from around 0.35 R$/kWh to about 0.69 R$/kWh. It is very important to highlight that the LCOE of this work is given in R$/kWh, so it is not possible to compare with LCOEs calculated in US$/kWh without a rate conversion.

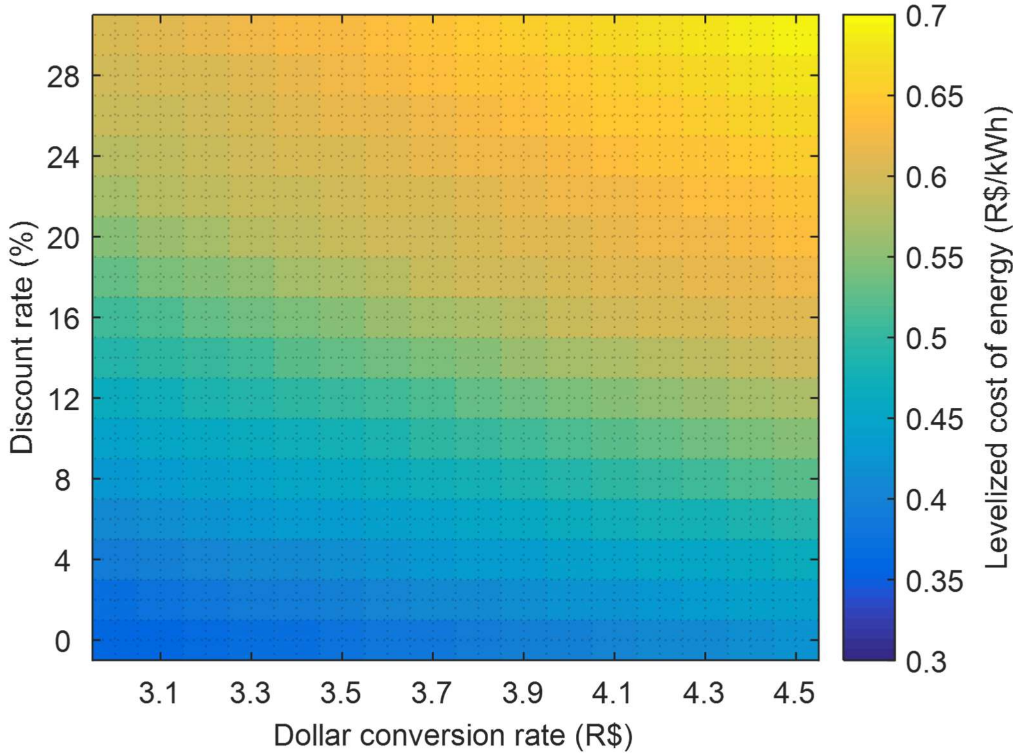
Finally, the primary energy ratio to each situation of NPV without taxes is presented in Figure 20, and it ranges from around 0.63 to around 0.69 with an approximate average of 0.69. Likewise, the primary energy ratio with taxes ranges also from about 0.63 to about 0.69, however the approximate average is 0.67, as can be seen in Figure 21. Thus, the PER average without taxes is slightly higher than when the taxes are considered. As a consequence, it is possible to conclude that the trigeneration system overall primary energy conversion efficiency does not suffer considerable influence of equipment taxes.

Figure 18 – Variation on levelized cost of energy at maximum net present values to the hospital case without equipment taxes



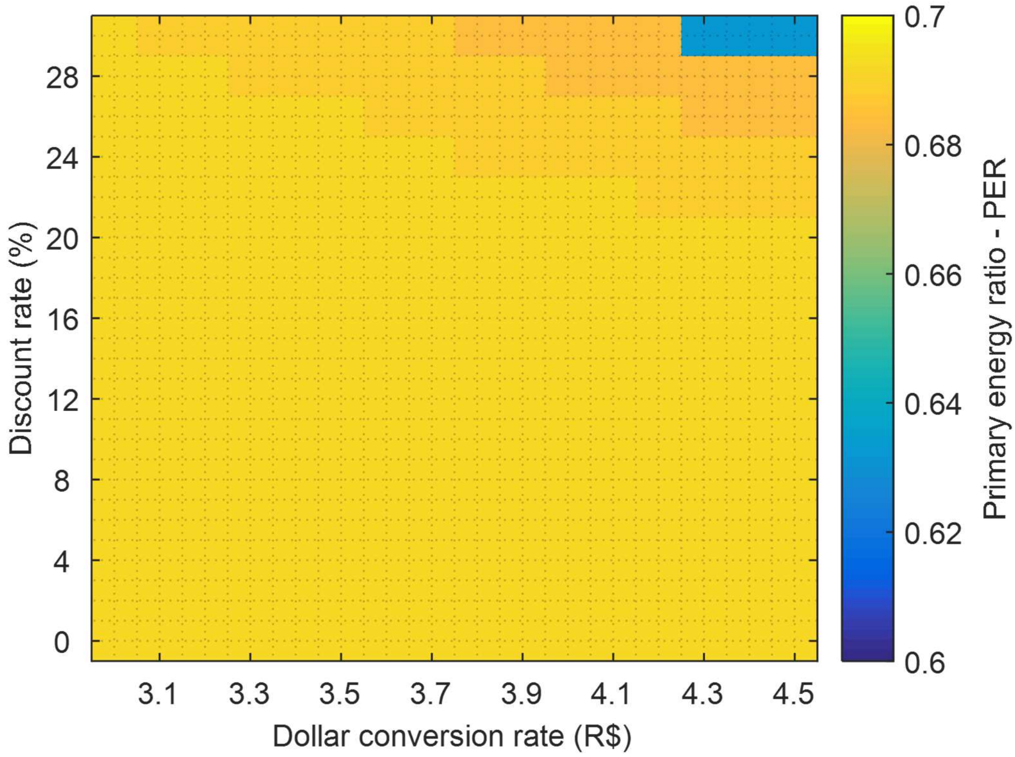
Source: Author

Figure 19 – Variation on levelized cost of energy at maximum net present values to the hospital case with equipment taxes



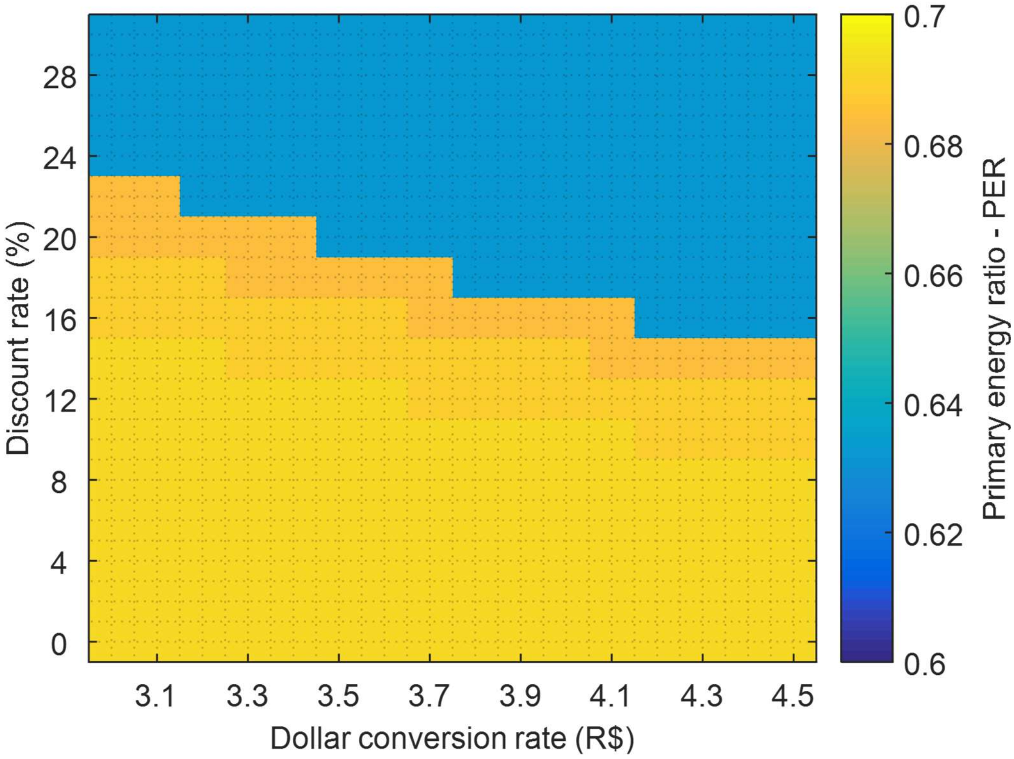
Source: Author

Figure 20 – Variation on primary energy ratio at maximum net present values to the hospital case without equipment taxes



Source: Author

Figure 21 – Variation on primary energy ratio at maximum net present values to the hospital case with equipment taxes



Source: Author

In summary, the presented study case 1 shows that trigeneration systems to hospitals can be profitable, but its profitability depends on economic indices which are not always ease to predict. Also, each case has different results, so a hospital with higher energy demand can shows itself more suitable to trigeneration systems than smaller ones. Moreover, if considered the use of national equipment in the system, the financial benefits would probably increase. Additionally, this work gives parameters to investors decide if Brazilian hospitals have or not potential to trigeneration systems, as each business has its own economical indexes they can use the sensitivity study to have a general idea of profitability. Obviously, a more detailed study has to be made, to have a more realistic view of financial benefits. So, from the financial point of view, it is possible to affirm that small and micro trigeneration systems in hospitals are on their threshold of viability. Although, not only the financial point of view shows potential advantages, but the energy side also can give support to decisions, as was presented, the primary energy conversion efficiency is high and the average grid dependence index is low. Another important point is that the policy and regulations play an important role in the adoption of those technologies, especially considering the related taxes and uncertainties about the investment.

3.3 CASE STUDY 2

The second discussed case is a hypothetical residential building located in Minas Gerais and connected to the low voltage network. The tariff scheme used by the residential building is named B1 residential custom tariff, which charges only the electric energy consumption [42]. Moreover, all the tariffs are already with taxes (ICMS, PASEP and COFINS) and it was also used the green flag value. The electricity tariffs (with taxes), and taxes used on this work are presented on Table 5 and they are from June, 2018 [32,43].

Table 5 – Demand and electricity tariffs, and taxes to study case 2

Taxes names	**ICMS**	**PASEP**	**COFINS**
Taxes (%)	30	0.56	1.90
Period		**All the time**	
Electricity tariff price – first year (R$/kWh)		0.8689	

Source: Companhia Energética de Minas Gerais - CEMIG, 2018

The natural gas tariff used by the residential building is also the cogeneration tariff, which has a fixed and a variable tariff. Moreover, all the tariffs are already with taxes (ICMS, PASEP and COFINS) and the variable tariff was converted to R$/kWh, as already explained. The fixed and variable natural gas tariffs with taxes, and the applied taxes percentage used on this work are presented in Table 6 (they are from June, 2018) [44].

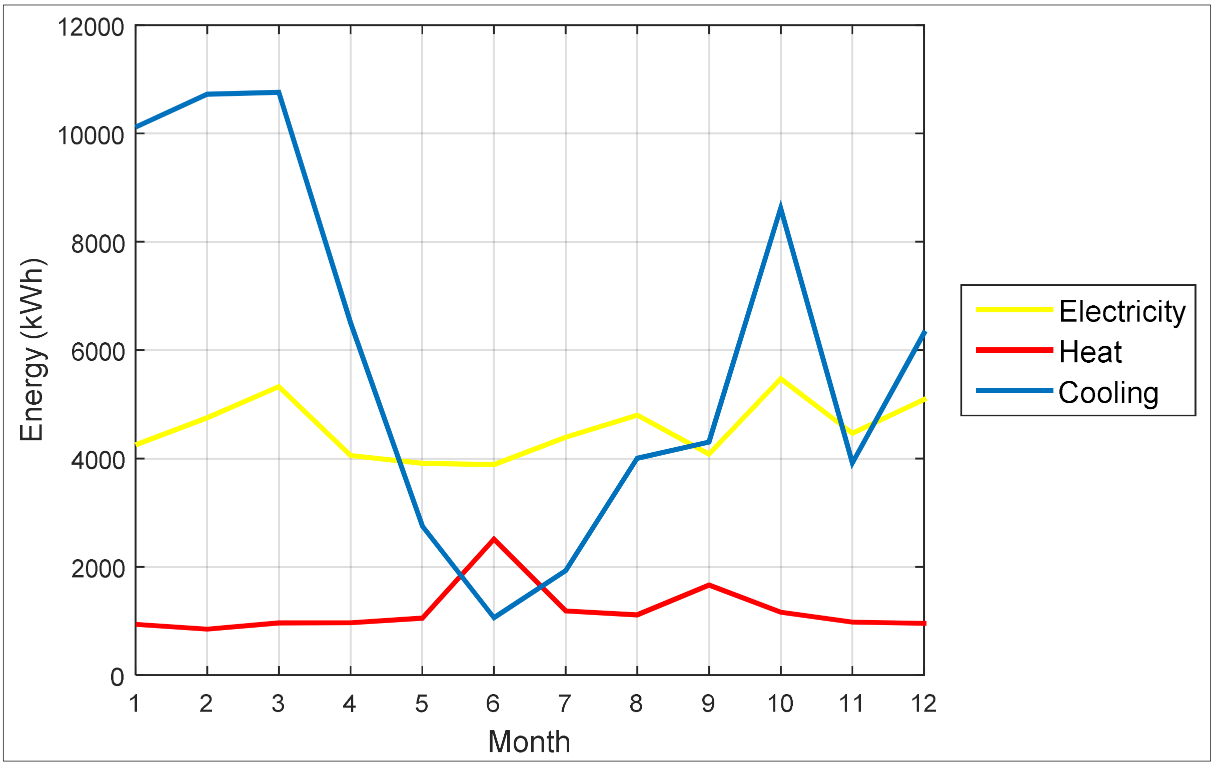
Table 6 – Fixed and variable natural gas tariffs, and taxes percentage to study case 2

Taxes names	**ICMS**	**PASEP**	**COFINS**
Taxes (%)	12	1.65	7.60
Tariffs		**Value**	
Natural gas tariff (R$/kWh)		0.18596	
Fixed natural gas tariff (R$)		99.69	

Source: Companhia de Gás de Minas Gerais - GASMIG, 2018

Moreover, the electricity consumption was estimated from an electricity bill of an apartment located in Juiz de Fora, Minas Gerais. On the other hand, the heat and cooling energy demand data was simulated by the program EnergyPlus considering the weather of Juiz de Fora and the building characteristics. The simulated building has 24 apartments distributed in three floors. In addition, the thermostat is set to cool the room that the temperature gets higher than 24 degrees Celsius, and to heat the room that gets colder than 18 degrees Celsius. Also, the hot water demand to shower is considered on simulations according to scheduled demand, and lastly, the whole system works all the time to keep rooms and hot water on predetermined temperatures. Figure 22 shows the energy demand of the building by month.

Figure 22 – Energy demand at the residential building



Source: Author

3.3.1 The Reference Case to the Study Case 2

As in the previous case, the reference case is electricity-based, the three energy demands (electricity, heating and cooling) of the residential building are summed into one electric load, always considering electric boiler and chiller efficiencies. Then, the electric energy tariff is applied over the consumed electricity to each month. It is important to remember that B1 residential custom tariff is applied (Table 5), and it is considered an annual readjustment on the electric energy price. The simulation is done according to the next section procedure.

3.3.2 The Detailed Optimisation Process to Study Case 2

The first important consideration to be made is that the lifespan of the system is 15 years, so to each simulation the number of calculated years will be limited to this value. Moreover, the discount rate (*discount_rate*) is varied from 0% to 15% in 1% steps, as well as, the US Dollar to Brazilian Real conversion price (*dollar*) is varied from R$3.00 to R$4.50 in R$0.10 steps. Equally important is the variation of the prime mover electric generation capacity (*Cpm*), from 0kW to 20kW in 5kW steps, and the boiler heat generation capacity (*boiler*), from 0kW to 50kW in 10kW steps.

Considering the given information about study case 2, it is possible to set the variables present on the flowchart explained in Figure 4. So, Table 7 shows the optimization flowchart variable values to study case 2.

Table 7 – Optimization flowchart variable values to study case 2

Variable	Value
ddiscount_rate	1%
mdiscount_rate	15%
dCpm	5 kW
mCpm	20 kW
dcboiler	10 kW
mboiler	50 kW

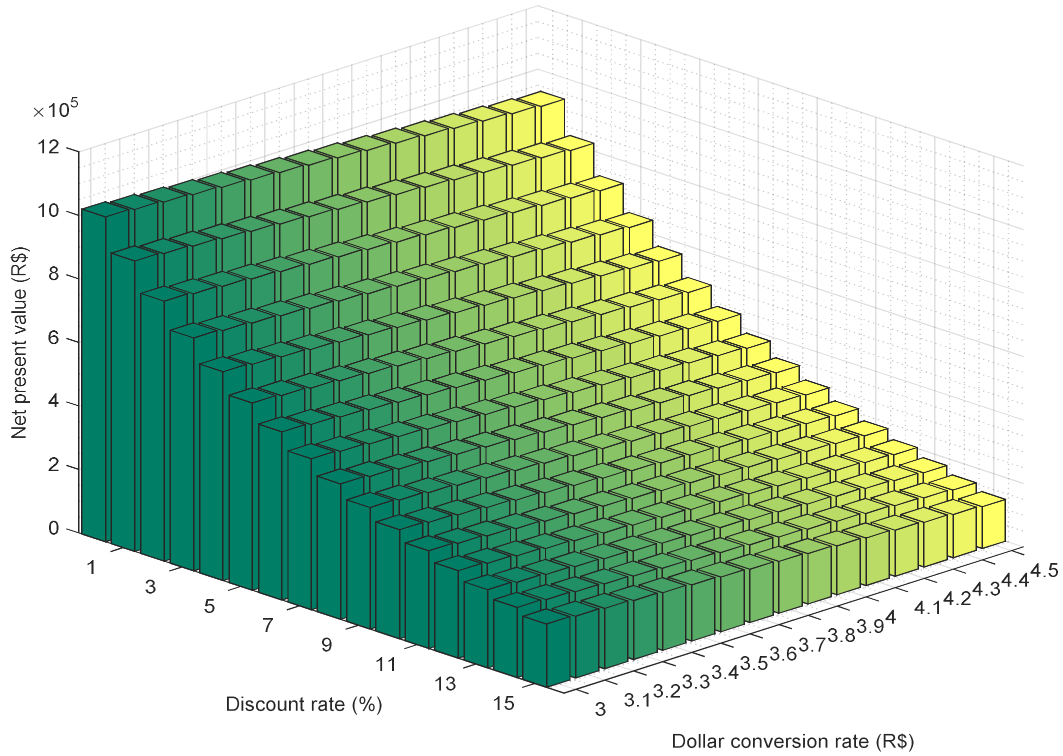
Source: Author

3.3.3 Results and Analysis to the Study Case 2

This section will present simulation results from the case 2, and then it will be analysed. In the first place, it will be presented the net present value sensitivity study, then the equivalent equipment sizing, the investment cost, the equivalent grid dependence index, the discounted payback time, the levelized cost of energy, and the primary energy ratio. All of them are simulated, firstly, without equipment taxes, and after, considering equipment taxes.

The first result to be presented and analysed is the net present value sensitivity study without equipment taxes. As it can be seen on Figure 23, the net present value decreases as the discount rate and US Dollar conversion rate increase. Also, the impact of rate variation on the NPV is higher with discount rate than with US Dollar. In general, the NPV is higher than zero in all the possible evaluated situations, therefore, considering the present case and the NPV only, the investment is safe and there is no risk of negative investment return. However, as it was not considered equipment taxes, the current scenario will change when considered taxes.

Figure 23 – Maximum net present values to the residential building case study without equipment taxes

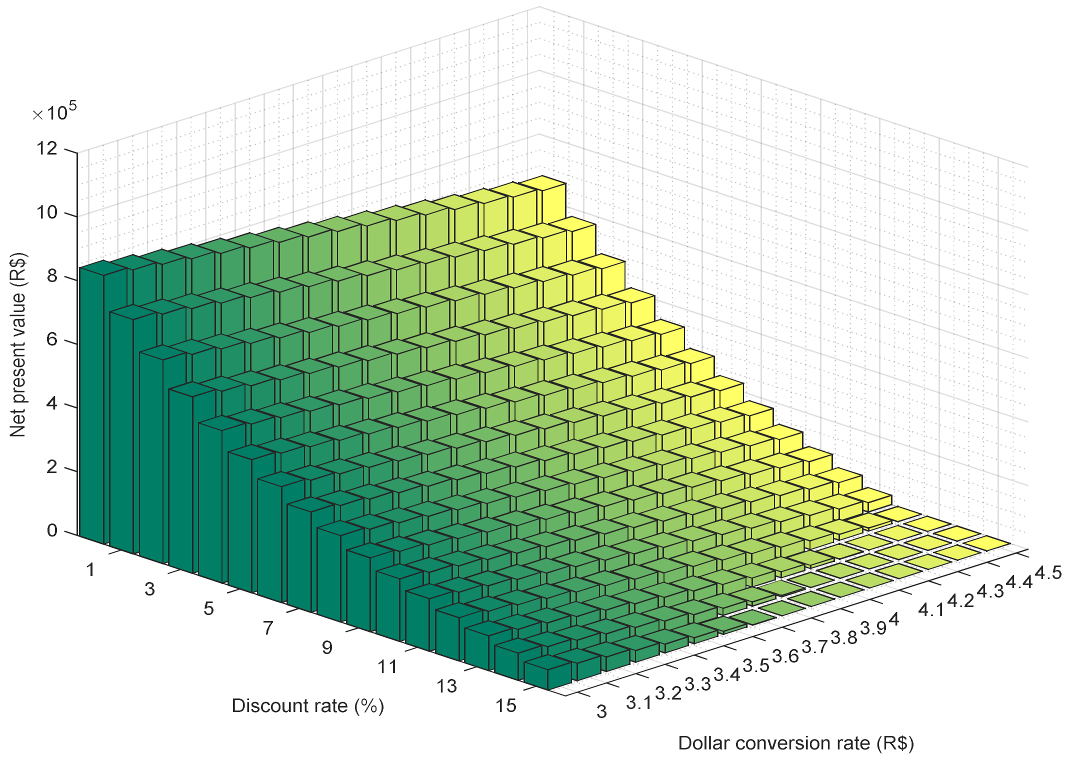


Source: Author

The second result to be presented and analysed is, obviously, the net present value sensitivity study with equipment taxes. As it can be seen on Figure 24, the net present value also decreases as the discount rate and US Dollar conversion rate increase, as expected. Moreover, the impact of rate variation on the NPV is also higher with discount rate than with US Dollar. This time, the NPV is higher than zero from 0% to 12% of discount rate and to any considered US Dollar conversion rate variation, so this is the safest region to investment as the dollar variation does not make the investment return negative. However, from 13% to 15% of discount rate, the positive NPV depends on the US Dollar conversion rate, therefore this region is riskier than the previous one.

Comparing the previous net present values sensitivity studies, the main difference is on the machinery investment price. In the first picture, the taxes imposed by the Brazilian government are ignored, consequently, the NPV is higher than in the second picture, which considers maximum estimated taxes (100%). It is easy to see the influence of taxes on the last two illustrations, in the first graphic the investment was 100% safe (considering the NPV only) if considered the studied range of discount rate and US Dollar, while in the second graphic the investment return depends on the situation. Therefore, once more, it can be concluded that Brazilian taxes limit the investment return on trigeneration systems.

Figure 24 – Maximum net present values to the residential building case study with equipment taxes

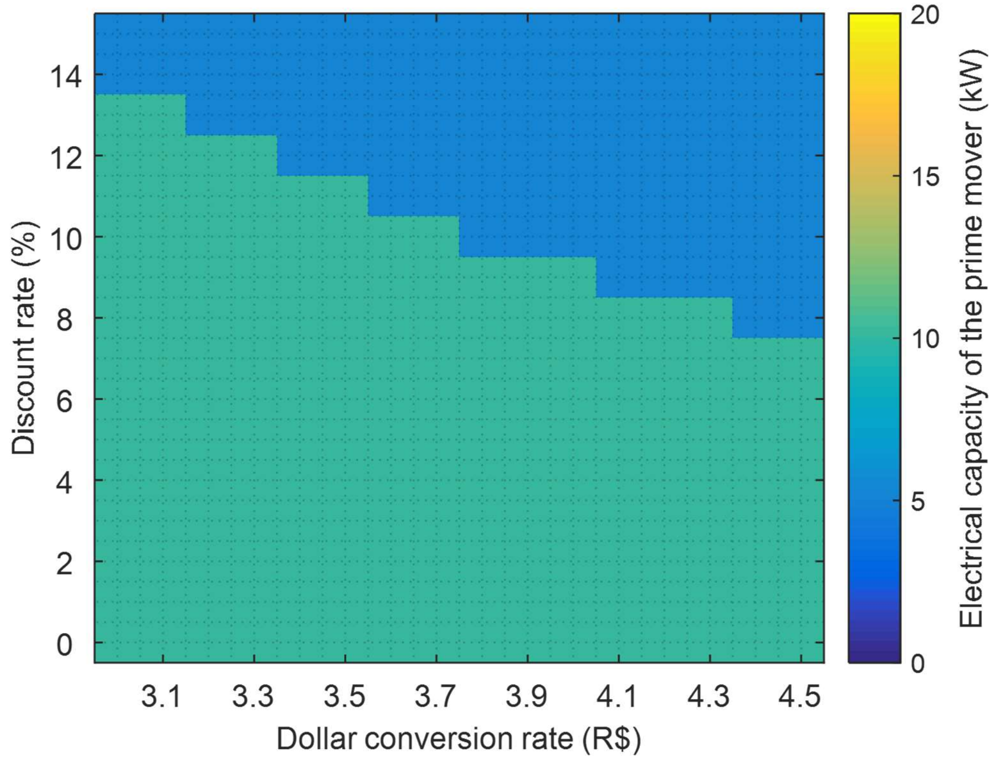


Source: Author

After the calculation of the maximum NPV, it is possible to evaluate the correspondent equipment sizing, the investment cost, the grid dependence index, the discounted payback, the levelized cost of energy, and the primary energy ratio. Thus, the sizing of electrical capacity of the prime mover and the boiler sizing to the maximum NPVs are presented in Figure 25 and Figure 26.

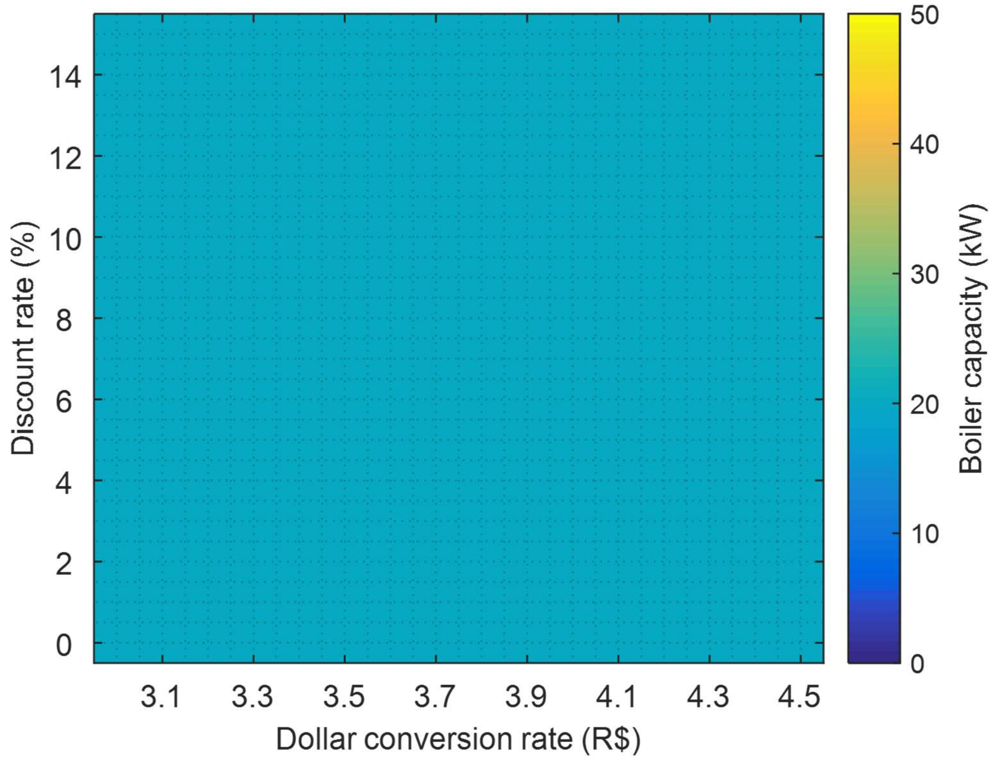
As can be seen on Figure 25 and Figure 26, the prime mover electric capacity has two possible optimal values, 5kW and 10kW, while the boiler can have 10kW or 20kW of heat capacity. The ideal capacity to the maximum NPV modifies to each discount rate and US Dollar conversion rate, as expected. Also, the boiler capacity of 20kW is selected as the best option in all situations, while the prime mover ideal sizing is 10kW in almost 68% of the situations. However, the selection of the best size to the system is a joint decision, so it cannot be independently decided.

Figure 25 – Sizing of the prime mover (electrical) at maximum net present values to the residential building case without equipment taxes



Source: Author

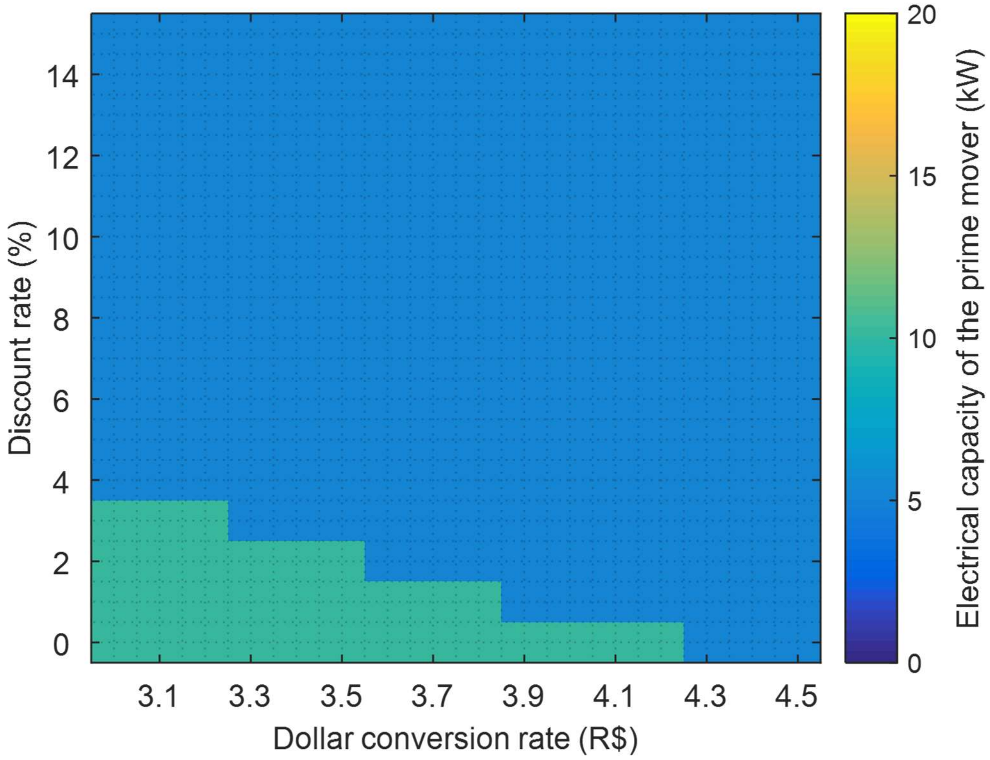
Figure 26 – Sizing of the boiler at maximum net present values to the residential building case without equipment taxes



Source: Author

The sizing results considering machinery taxes are presented on Figure 27 and Figure 28. These pictures show the predominance of 5kW prime mover as the best option in approximately 86% of the situations and 20kW boiler as the best option in 100% of the situations.

Figure 27 – Sizing of the prime mover (electrical) at maximum net present values to the residential building case with equipment taxes

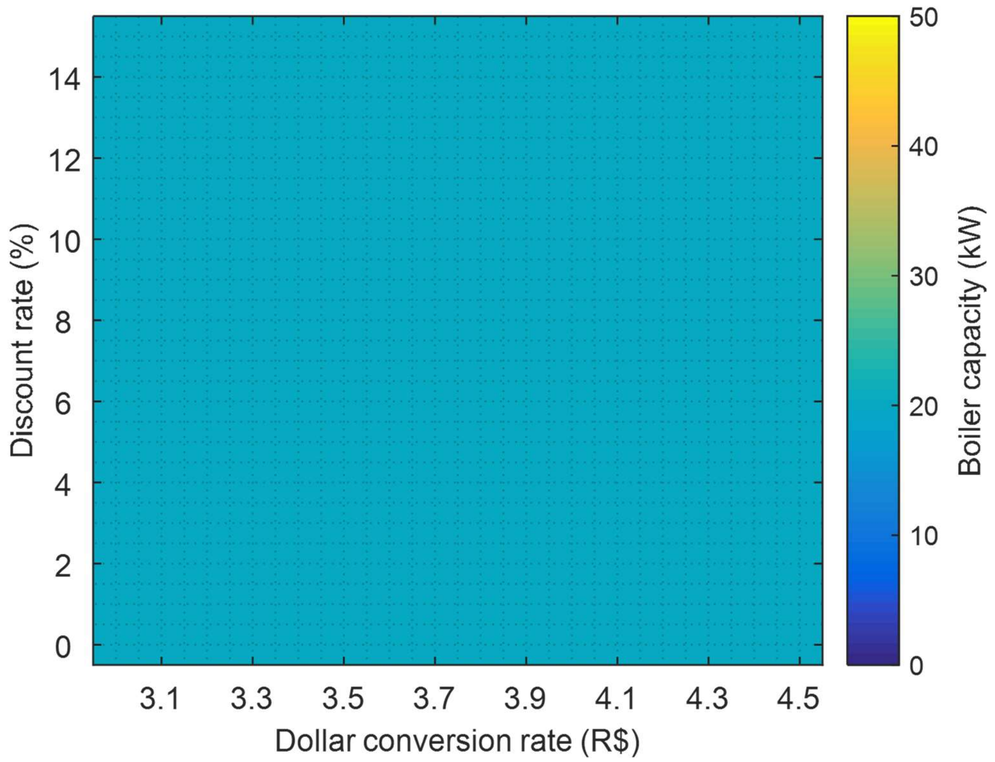


Source: Author

From the prime mover and boiler sizing, together with the absorption chiller size, it is possible to obtain the equipment investment cost. So, it is shown in Figure 29 the investment cost without taxes and in Figure 30 the same cost considering taxes. The average investment cost without taxes is around R$ 205 thousand, while the taxes rise the average investment cost to around R$ 350 thousand.

Figure 31 shows the grid dependence index of the building at maximum net present values without equipment taxes. In general, the GDI is very low, with 100% of situations below 16% of dependence from the external grid. However, the building will always need external network electricity to complement its demand. This small network dependence is enough to cover the minimal use of electricity charged on the B1 residential custom tariff system to stay connected to the network (availability tariff). Therefore, due to high electricity costs, the optimisation indicates that the CCHP system should work with minimum power from the external network.

Figure 28 – Sizing of the boiler at maximum net present values to the residential building case with equipment taxes

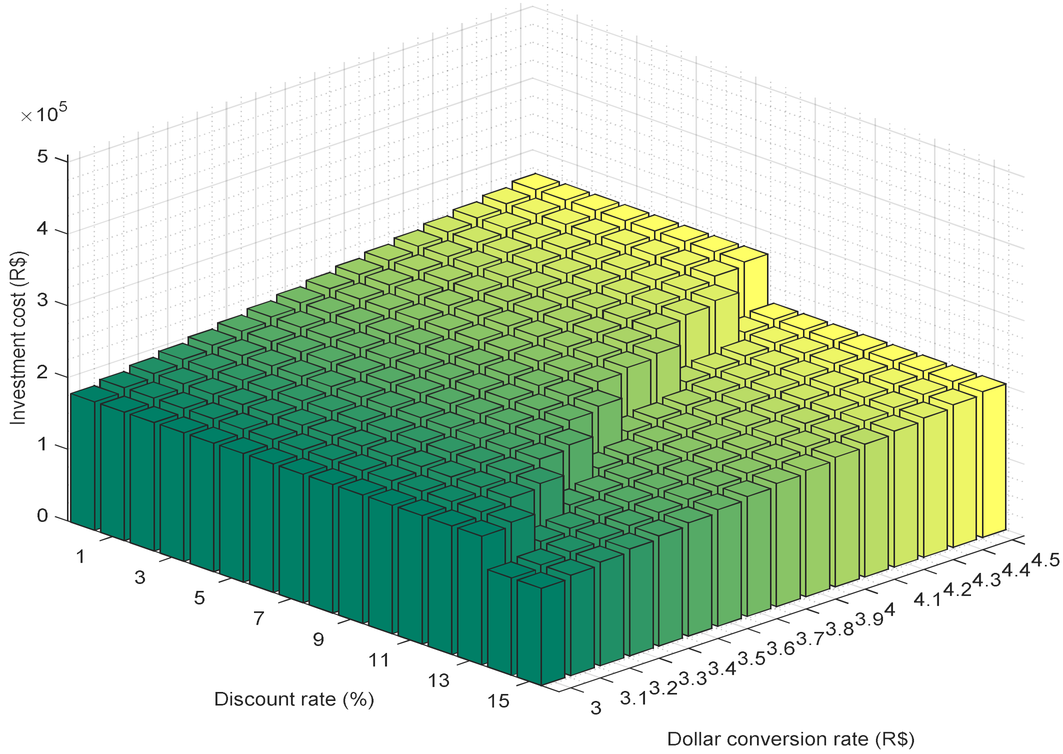


Source: Author

Now, Figure 32 shows the result of grid dependence index for the building at maximum net present values with equipment taxes. Following the same pattern from the previous presented grid dependence, the GDI with equipment taxes is still very low in all situations, which are below 16%. However, at this time, most of the situations have a GDI close to 16%, while only in few situations the index is around 7%, different from the previous presented index.

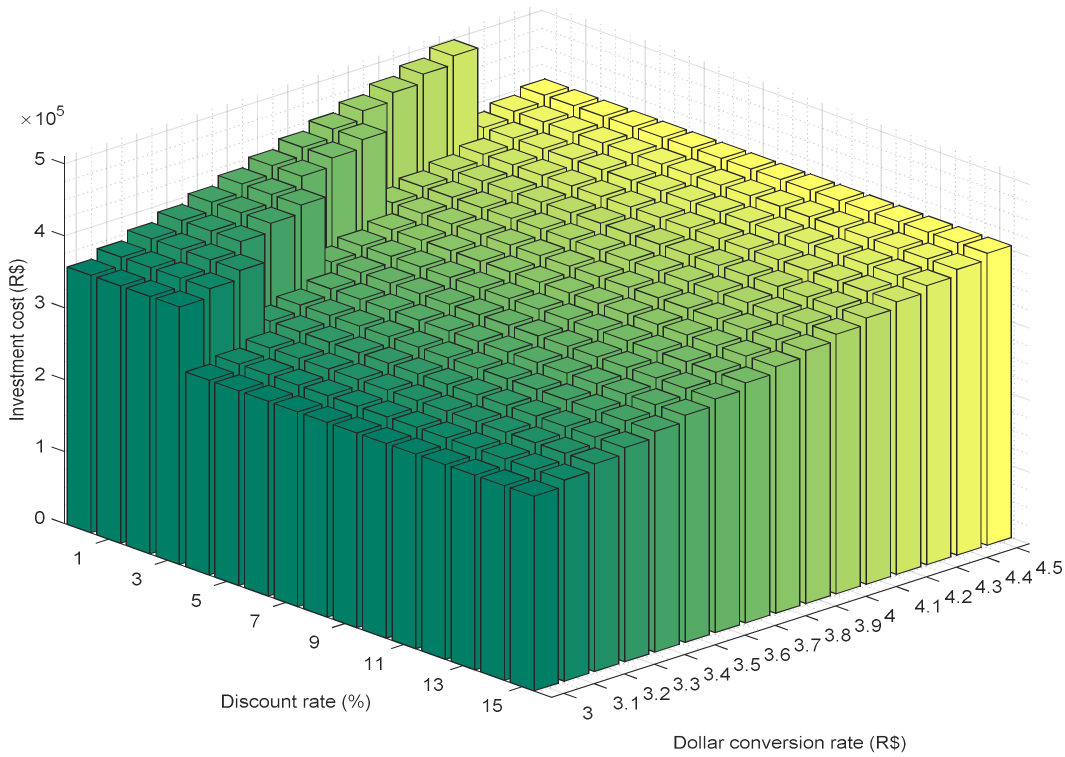
From comparison between the two GDIs sensitivity studies, it is possible to observe that in both simulations the grid dependence is low in all economic situation, so the CCHP system is responsible to supply most of the energy load. It can be really important to residential buildings that are located in regions where the electricity service provider cannot guarantee continuous electricity supply.

Figure 29 – Variation on investment cost at maximum net present values to the residential building case without equipment taxes



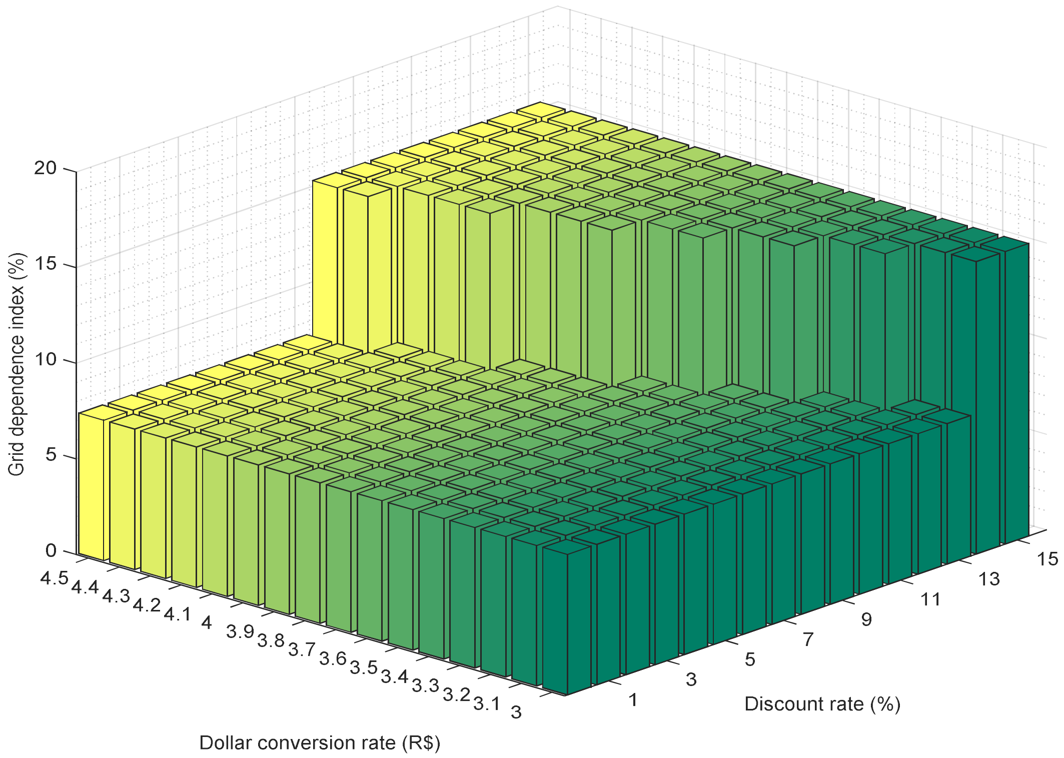
Source: Author

Figure 30 – Variation on investment cost at maximum net present values to the residential building case with equipment taxes



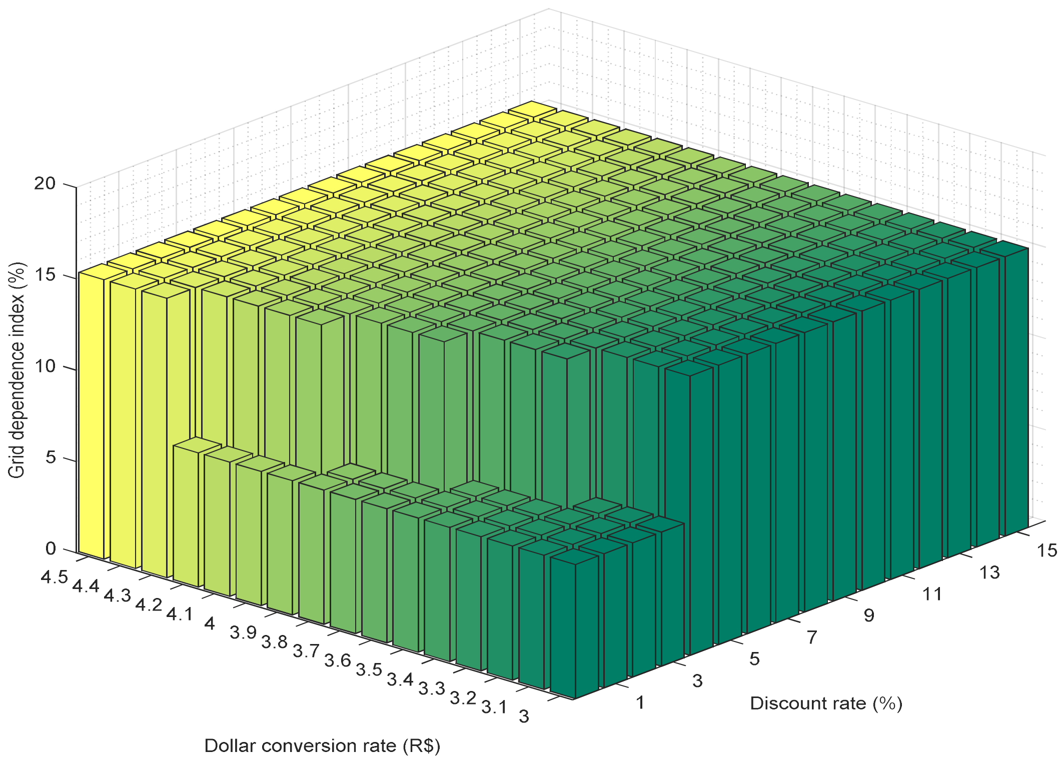
Source: Author

Figure 31 – Variation on grid dependence index at maximum net present values to the residential building case without equipment taxes



Source: Author

Figure 32 – Variation on grid dependence index at maximum net present values to the residential building case with equipment taxes

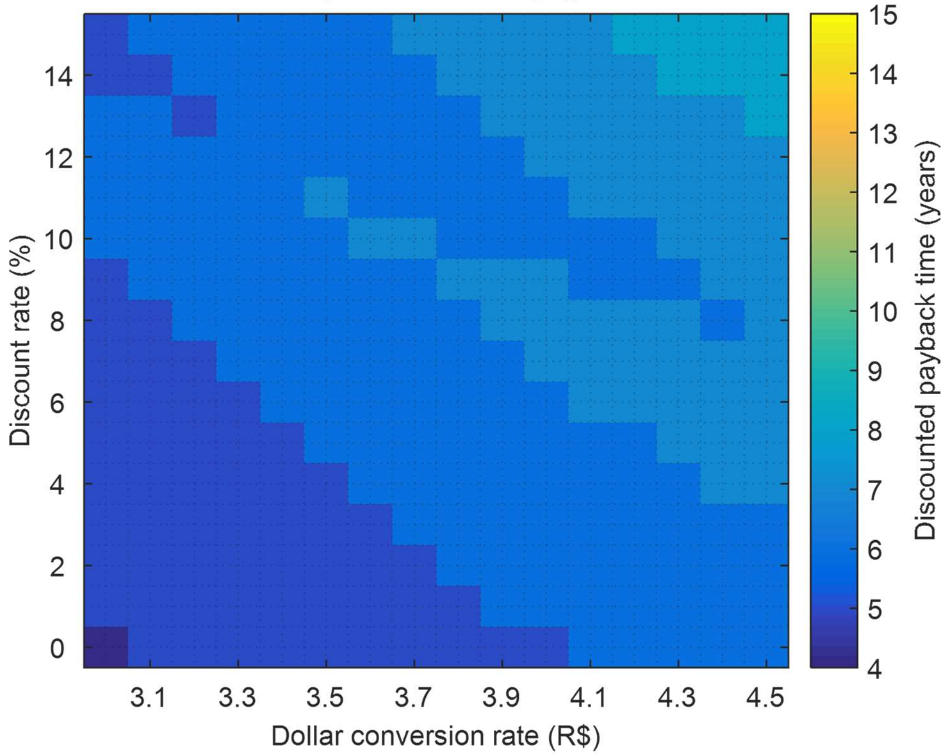


Source: Author

The discounted payback time without equipment taxes is presented on Figure 33. It can be observed that the minimum discounted payback time is 4 years and the maximum is 8 years. As residential buildings do not have commercial purposes (profit purposes), they can be considered good results. So, resident investors could have their attention drawn to such investment opportunity.

Figure 34 shows the discounted payback time with equipment taxes. From the point of view of a resident investor, more than three quarters of the situations are not financially beneficial, as great number of situations have discounted payback time higher than 8 years. While around 22% have payback time between 7 and 8 years, which could attract those specific investors' attention.

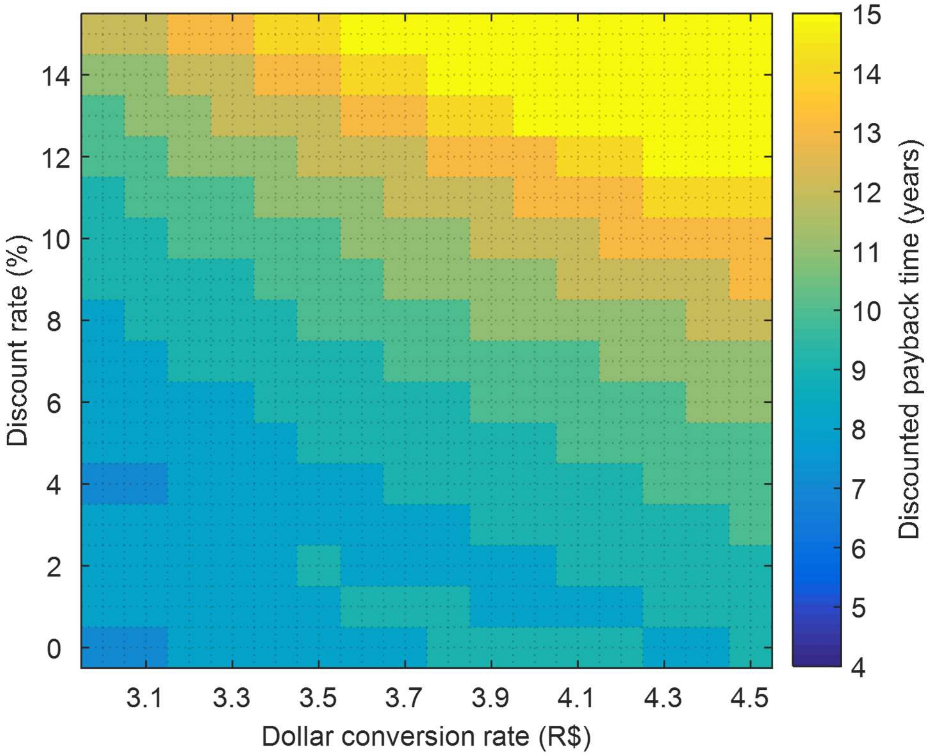
Figure 33 – Variation on discounted payback at maximum net present values to the residential building case without equipment taxes



Source: Author

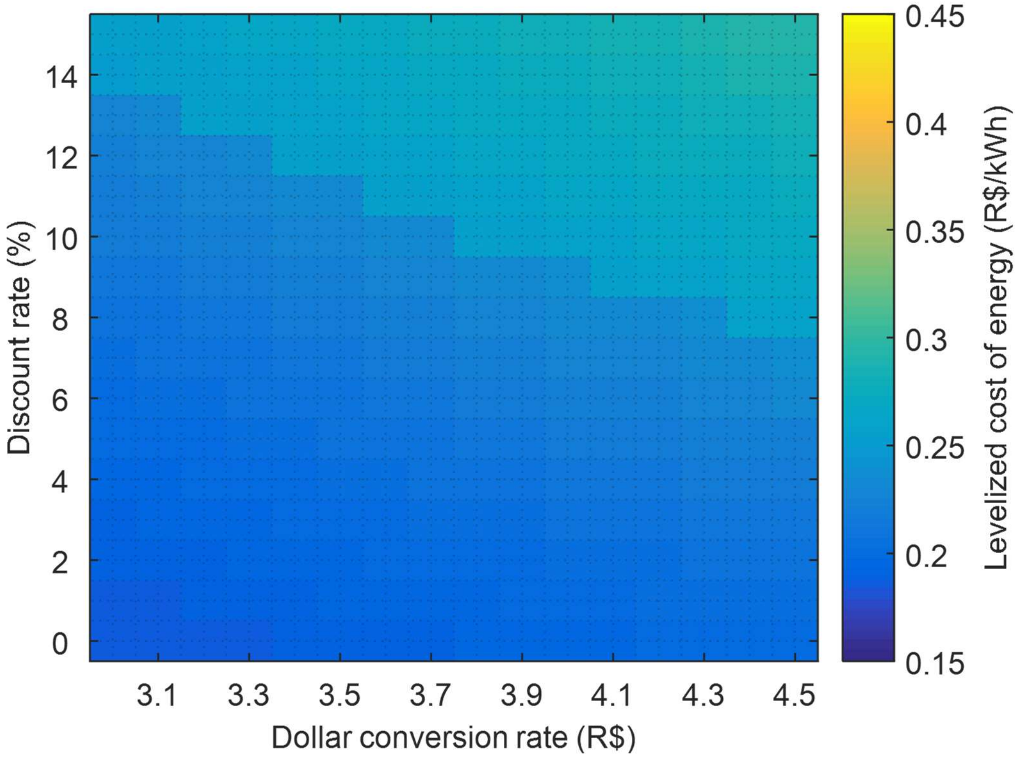
In concern of levelized cost of energy, Figure 35 shows possible values in the simulation without taxes, thus, it ranges from around 0.18 R$/kWh to around 0.29 R$/kWh with an average of 0.23 R$/kWh, which are good results. In contrast, the simulation considering taxes has higher values to LCOE (Figure 36), and it ranges from about 0.22 R$/kWh to about 0.41R$/kWh with an average value of 0.31 R$/kWh, which are reasonable results.

Figure 34 – Variation on discounted payback at maximum net present values to the residential building case with equipment taxes



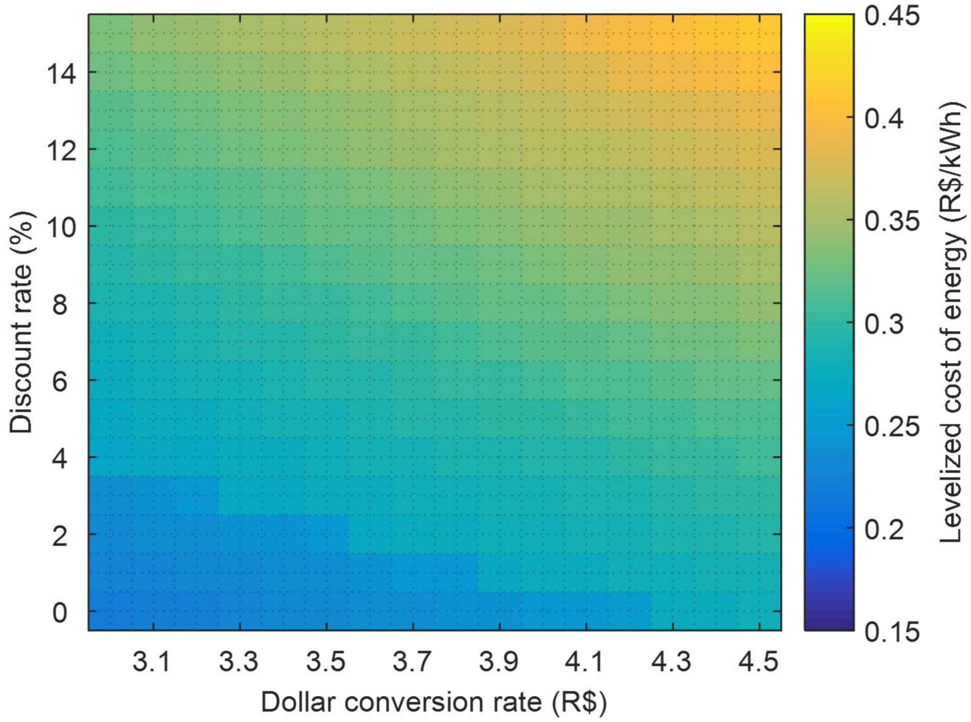
Source: Author

Figure 35 – Variation on levelized cost of energy at maximum net present values to the residential building case without equipment taxes



Source: Author

Figure 36 – Variation on levelized cost of energy at maximum net present values to the residential building case with equipment taxes

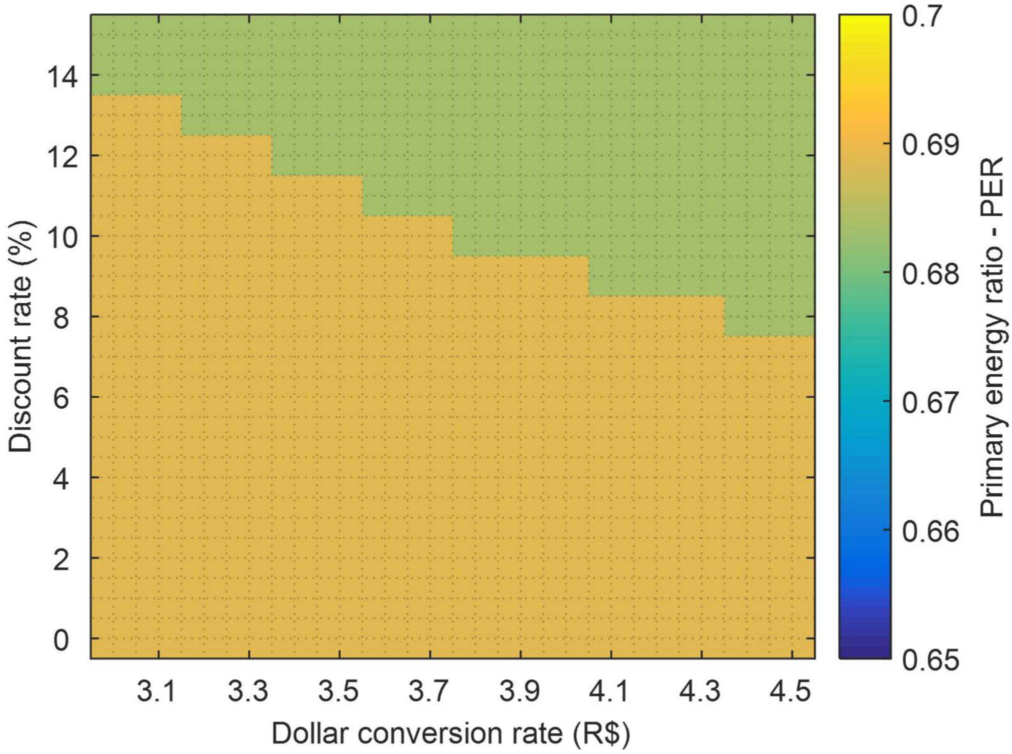


Source: Author

Now, the primary energy ratio without taxes is shown in Figure 37. Its variation is not considerable, so it is presented only its average, which is approximately 0.69. Similarly, the PER with taxes is approximately 0.68, as shown in Figure 38. As observed, the Brazilian taxes have near null effect on the primary energy ratio, as expected.

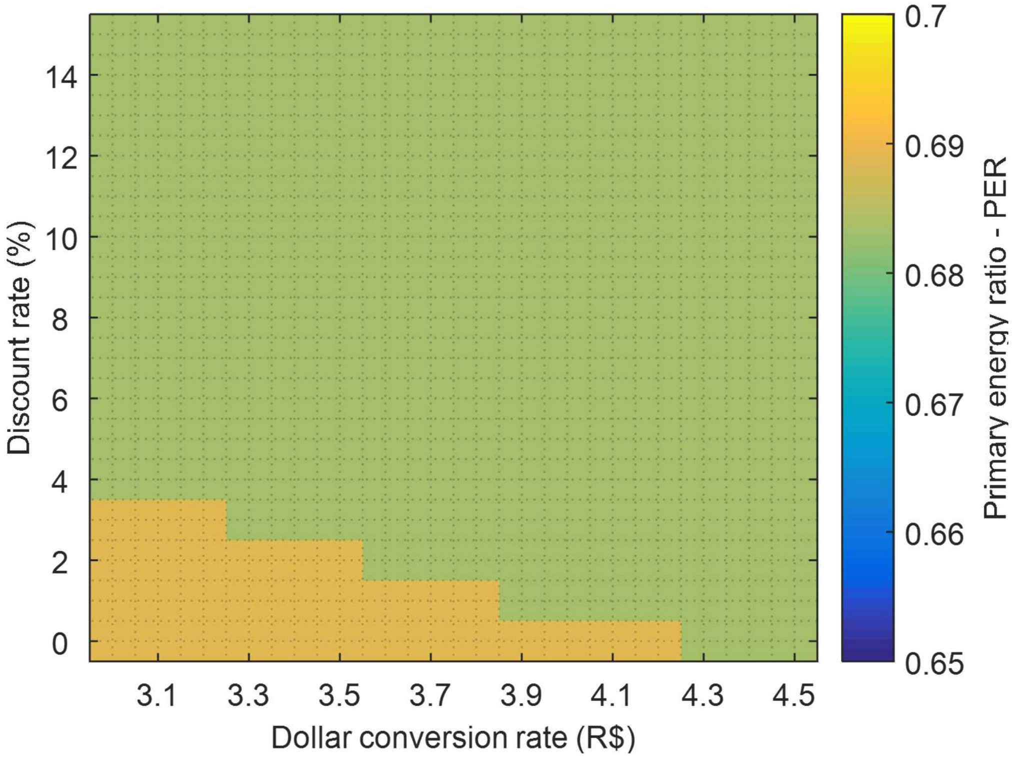
In summary, the presented study case 2 shows that trigeneration systems to residential buildings are profitable to the current Brazilian economic scenario, although their profitability depends on economical indices and political decisions, which are not always ease to predict. Also, each case has different results, so a residential building with distinct characteristics could be more suitable to trigeneration systems than others. Moreover, if considered the use of national equipment to the system, the financial benefits would probably increase. In addition, this work gives parameters to investors decide if Brazilian residential buildings have or not potential to trigeneration systems, so they can use the sensitivity study to have an idea of profitability. In fact, a more detailed study has to be made in order to have a more realistic picture of financial benefits. Finally, not only the financial point of view shows advantages, but the energy side also can give support to decisions, as was presented, the energy efficiency is high, the grid dependence index is low and the levelized cost of energy is considerably good.

Figure 37 – Variation on primary energy ratio at maximum net present values to the residential building case without equipment taxes



Source: Author

Figure 38 – Variation on primary energy ratio at maximum net present values to the residential building case with equipment taxes



Source: Author

3.4 CASE STUDY 3

The third discussed case is a postgraduate building located in Juiz de Fora, Minas Gerais, and connected to the medium voltage network. The tariff policy applied over the electricity consumption of the building is named A4 green tariff, which has one fixed demand price and the electric energy tariff is time-of-use based [42]. Moreover, all the tariffs are already with taxes (ICMS, PASEP and COFINS), and the green flag is used in this work. The demand and electric energy tariffs, and taxes used on this work are presented in Table 8 and they are from June, 2018 [32,43].

Table 8 – Demand and electricity tariffs, and taxes to study case 3

Taxes names	**ICMS**	**PASEP**	**COFINS**
Taxes (%)	6	0.56	1.90
Time of use periods	**From 0h to 18h**	**From 18h to 21h**	**From 21h to 0h**
Electricity tariff price – first year (R$/kWh)	0.3527	1.6860	0.3527
Demand price (R$/kW)	15.9384	15.9384	15.9384

Source: Companhia Energética de Minas Gerais - CEMIG, 2018

The natural gas tariff used by the postgraduate building is also the cogeneration tariff, which has a fixed and a variable tariff. Moreover, all the tariffs are already with taxes (ICMS, PASEP and COFINS) and the variable tariff was converted to R$/kWh, as already explained. The fixed and variable natural gas tariffs with taxes, and the applied taxes percentage used on this work are presented in Table 9 (they are from June, 2018) [44].

Table 9 – Fixed and variable natural gas tariffs, and taxes percentage to study case 3

Taxes names	**ICMS**	**PASEP**	**COFINS**
Taxes (%)	12	1.65	7.60
Tariffs		**Value**	
Natural gas tariff (R$/kWh)		0.18596	
Fixed natural gas tariff (R$)		99.69	

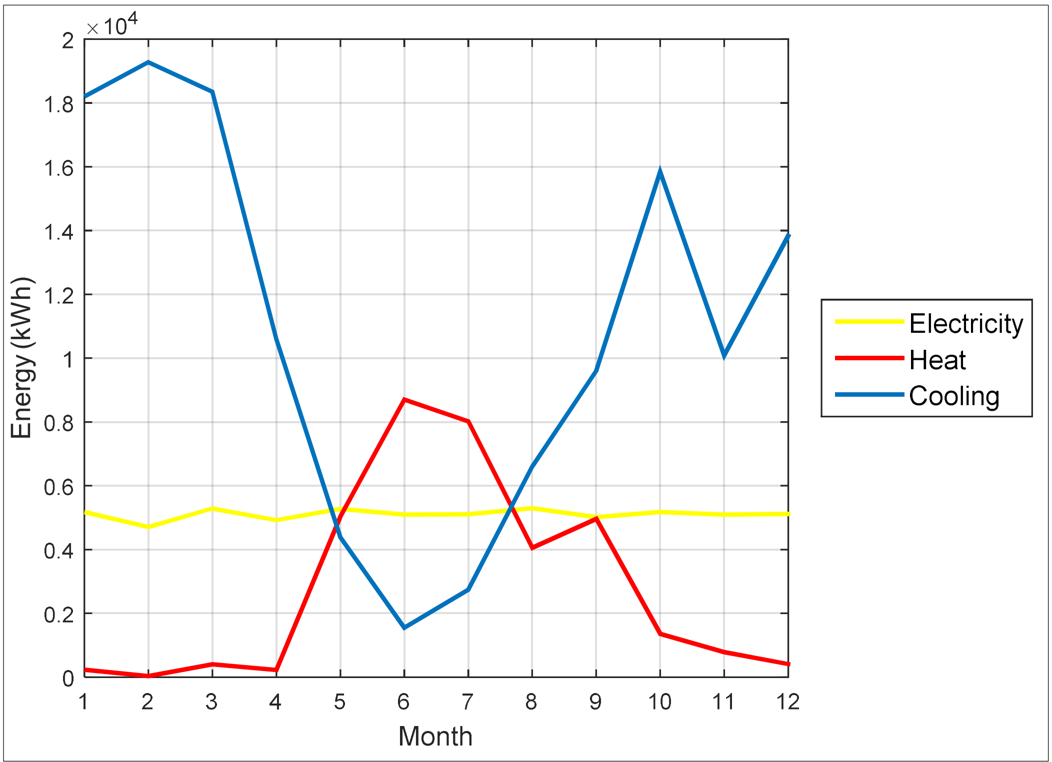
Source: Companhia de Gás de Minas Gerais - GASMIG, 2018

In addition, the electricity demand data was collected on site during one week, then the data was processed to find an average electricity demand per month according to hourly consumption of each week day. On the other hand, the heat and cooling energy demand data was simulated by the software EnergyPlus considering the building characteristics and the weather of Juiz de Fora, Minas Gerais. Also, the thermostat is set to cool the building when temperature gets higher than 24 degrees Celsius, and to heat the building when it gets colder than 18 degrees Celsius. Lastly, the data was processed to fit the input format of the algorithm and the final demand is shown in Figure 39.

3.4.1 The Reference Case to the Study Case 3

As the reference case is electricity-based, the three energy demands (electricity, heating and cooling) of the postgraduate building are summed into one electric load, always considering electric boiler and chiller efficiencies. Then, the electric energy tariff is applied over the consumed electricity to each month, and the demand tariff is applied to the maximum demand of each month. In this case, the green tariff prices to federal universities are applied (Table 8), also, it is considered annual readjustment on the electricity price. The simulation is done according to the next section procedure.

Figure 39 – Energy demand at the postgraduate building



Source: Author

3.4.2 The Detailed Optimisation Process to Study Case 3

The first consideration about this case is that the considered lifespan of the system is 15 years, so to each simulation the number of calculated years will be limited to this value. Moreover, the discount rate (*discount_rate*) is varied from 0% to 15% in 1% steps, as well as, the US Dollar to Brazilian Real conversion price (*dollar*) is varied from R$3.00 to R$4.50 in

R$0.10 steps. Similarly, there is the variation of the prime mover electric generation capacity (*Cpm*), from 0kW to 20kW in 5kW steps, and the boiler heat generation capacity (*boiler*), from 0kW to 60kW in 10kW steps.

Considering the given information about study case 3, it is possible to set the variables present on the flowchart explained in Figure 4. So, Table 10 shows the optimization flowchart variable values to study case 3.

Table 10 – Optimization flowchart variable values to study case 3

Variable	Value
ddiscount_rate	1%
mdiscount_rate	15%
dCpm	5 kW
mCpm	20 kW
dcboiler	10 kW
mboiler	60 kW

Source: Author

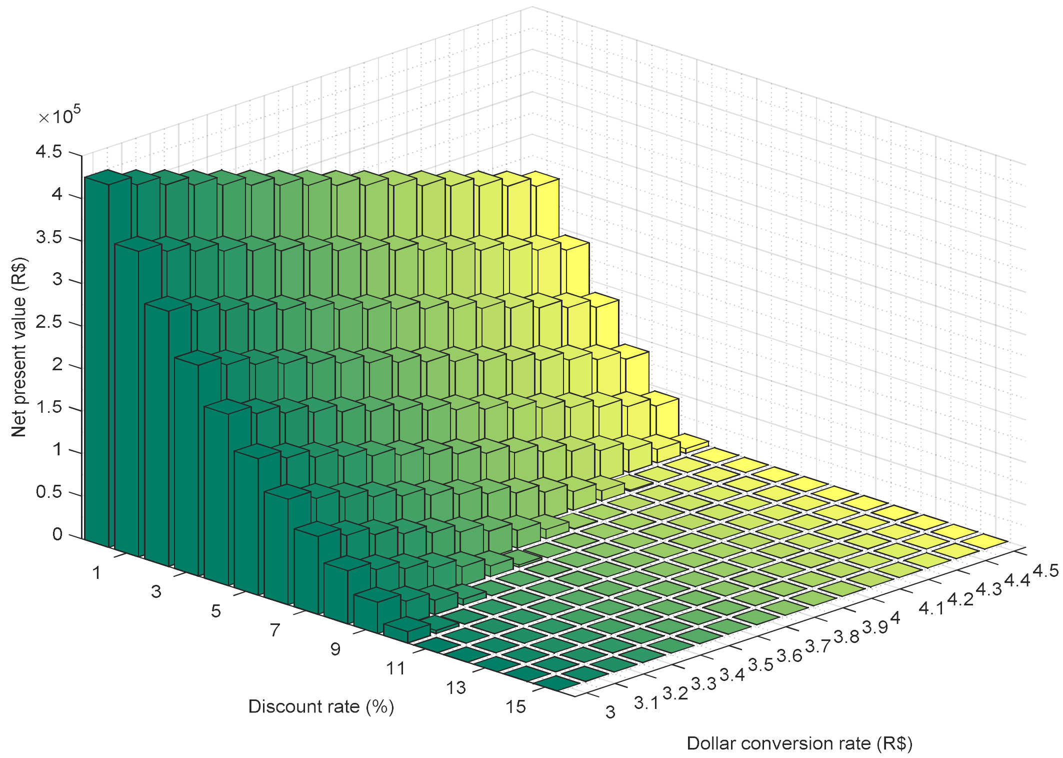
3.4.3 Results and Analysis to the Study Case 3

This section will present simulation results from the case 3, and then it will be analysed. In the first place, it will be presented the net present value sensitivity study, and then, the equivalent equipment sizing, the investment cost, the equivalent grid dependence index, the discounted payback time, the levelized cost of energy, and the primary energy ratio. All of them are simulated, firstly, without equipment taxes, and after, considering equipment taxes.

The first result to be presented and analysed is the net present value sensitivity study without equipment taxes. As it can be seen in Figure 40, the net present value decreases as the discount rate and US Dollar conversion rate increase. Also, the impact of rate variation on the NPV is higher with discount rate than with US Dollar. In general, the NPV is higher than zero from 0% to 5% of discount rate and to any considered US Dollar conversion rate variation, so this is the safest region to investment as the US Dollar variation does not make the NPV negative. However, from 6% to 10% of discount rate, the positive NPV depends on the US Dollar conversion rate, therefore this region is riskier than the previous one. Otherwise, discount rates equal or higher than 11% gives no financial benefit on the investment.

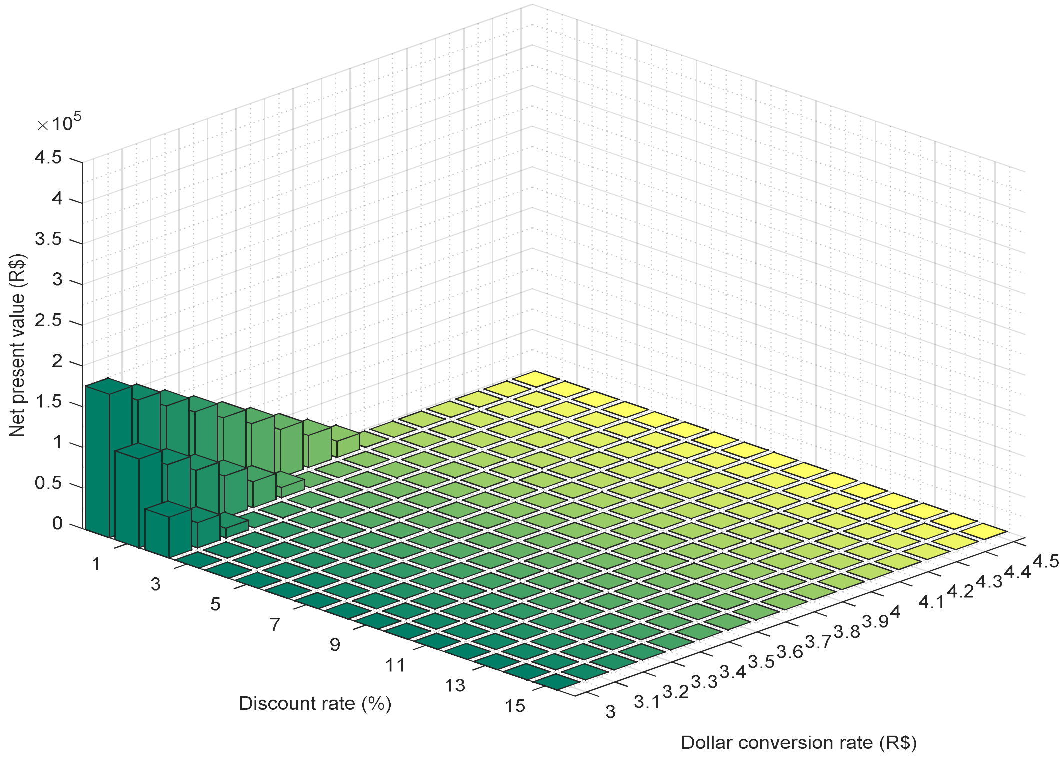
The second result to be presented and analysed is the net present value sensitivity study with equipment taxes. As it can be seen on Figure 41, the net present value also decreases as the discount rate and US Dollar conversion rate increase, as expected. Moreover, the impact of rate variation on the NPV is also higher with discount rate than with US Dollar. In general, the NPV is higher than zero from 0% to 2% of discount rate and the positive NPV depends on the US Dollar conversion rate, therefore this region is risky, but can have benefits. Otherwise, discount rates from 3% to 15% give no financial benefit on the investment.

Figure 40 – Maximum net present values to the postgraduate building case study without equipment taxes



Source: Author

Figure 41 – Maximum net present values to the postgraduate building case study with equipment taxes

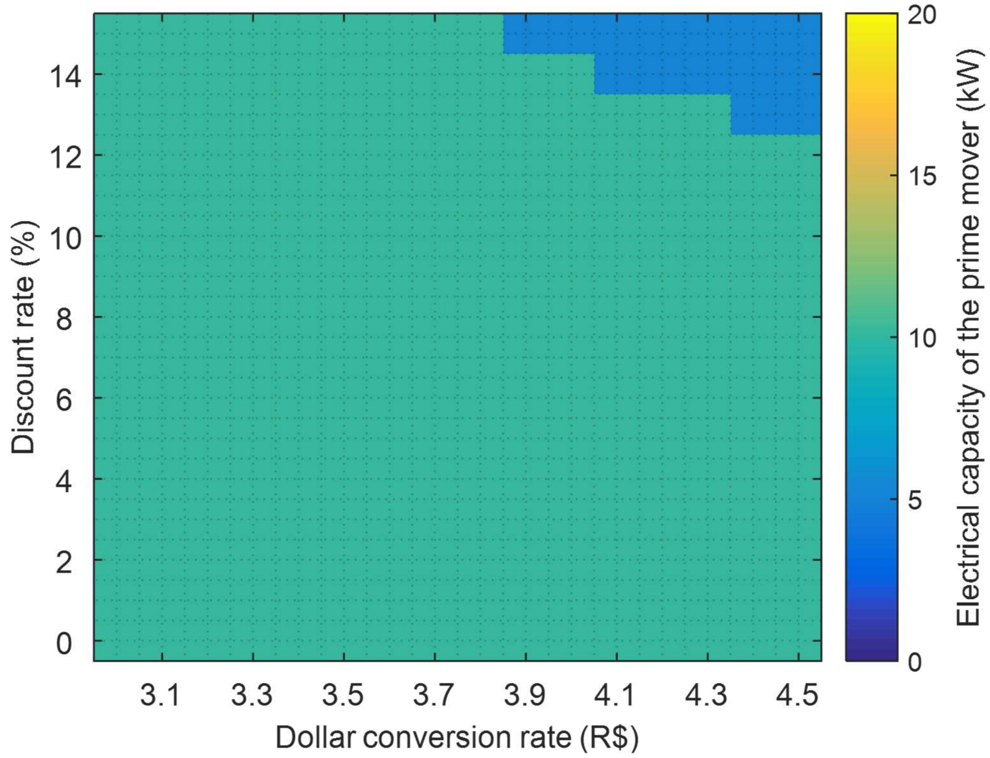


Source: Author

Comparing the previous net present values sensitivity studies, the only input difference is on the machinery investment price. In the first situation, taxes imposed by the Brazilian government are ignored, consequently, the NPV is higher than in the second situation, which considers maximum estimated taxes (100%). Therefore, the same conclusions made in the other study cases can be made, in other words, Brazilian taxes limit the investment return on trigeneration systems.

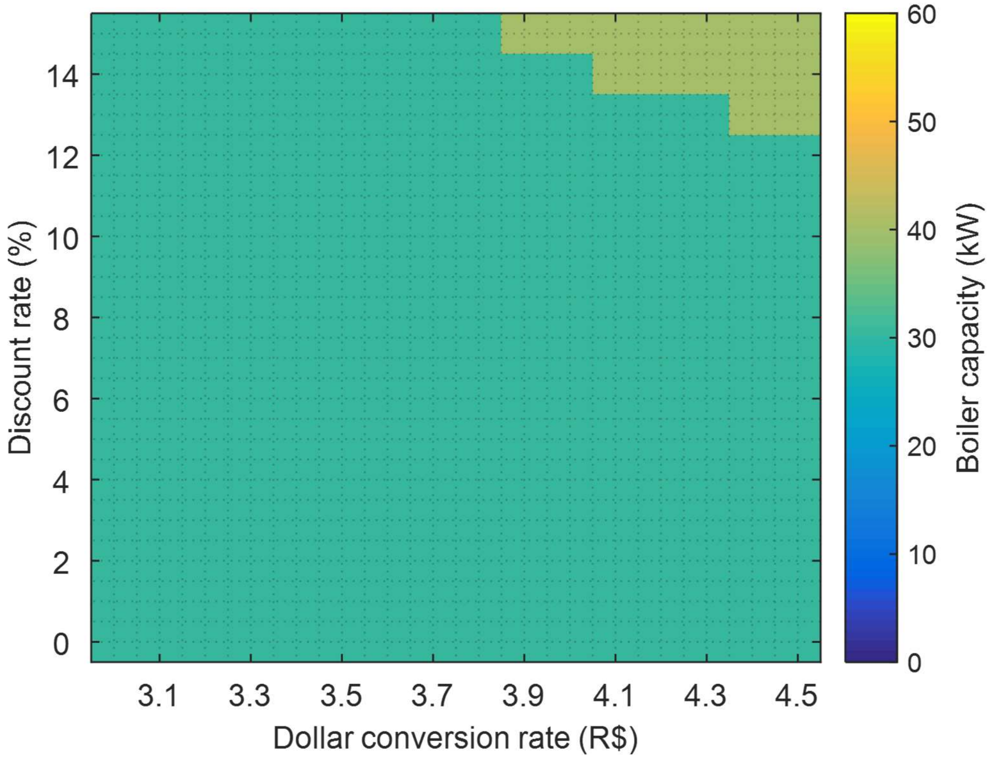
After the decision of the highest available NPVs, it is possible to find specific size of the three components of the trigeneration system, the investment cost, the grid dependence index, the payback time, the levelized cost of energy, and the primary energy ratio related to maximum NPVs. Therefore, the prime mover sizing (electrical) and boiler sizing to the postgraduate case without equipment taxes are presented in Figure 42 and Figure 43, respectively. Also, the absorption chiller size corresponds to the maximum cooling demand of the building, as it is not optimised there is no sizing study to absorption chillers on this work.

Figure 42 – Sizing of the prime mover (electrical) at maximum net present values to the postgraduate building case without equipment taxes



Source: Author

Figure 43 – Sizing of the boiler at maximum net present values to the postgraduate building case without equipment taxes



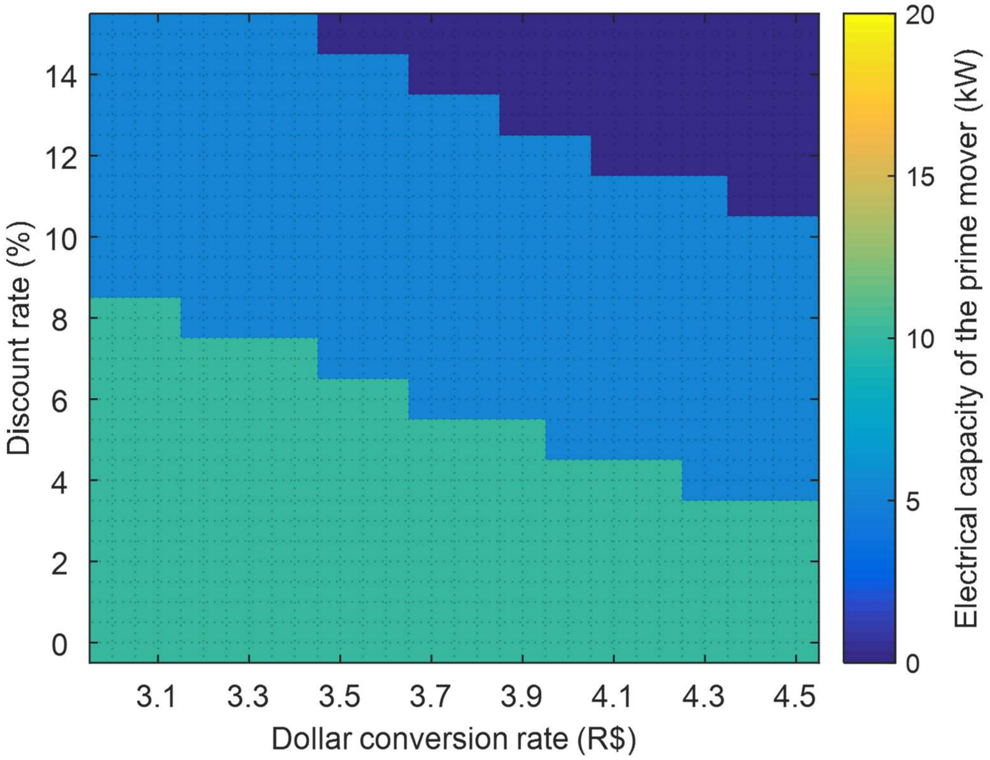
Source: Author

In general, prime mover capacity decreases as the discount rate and US Dollar conversion rate increases, thus, the prime mover sizing can go from 5kW to 10kW. In contrast, the boiler sizing capacity increases as the discount rate and US Dollar conversion rate increases, and its capacity can range from 30kW to 40kW.

If a comparison is made between the prime mover and boiler sizing capacities, it is possible to conclude that the prime mover size is complementary to the boiler size. In other words, when the prime mover is at its higher capacity, the boiler is at its lower capacity and vice versa.

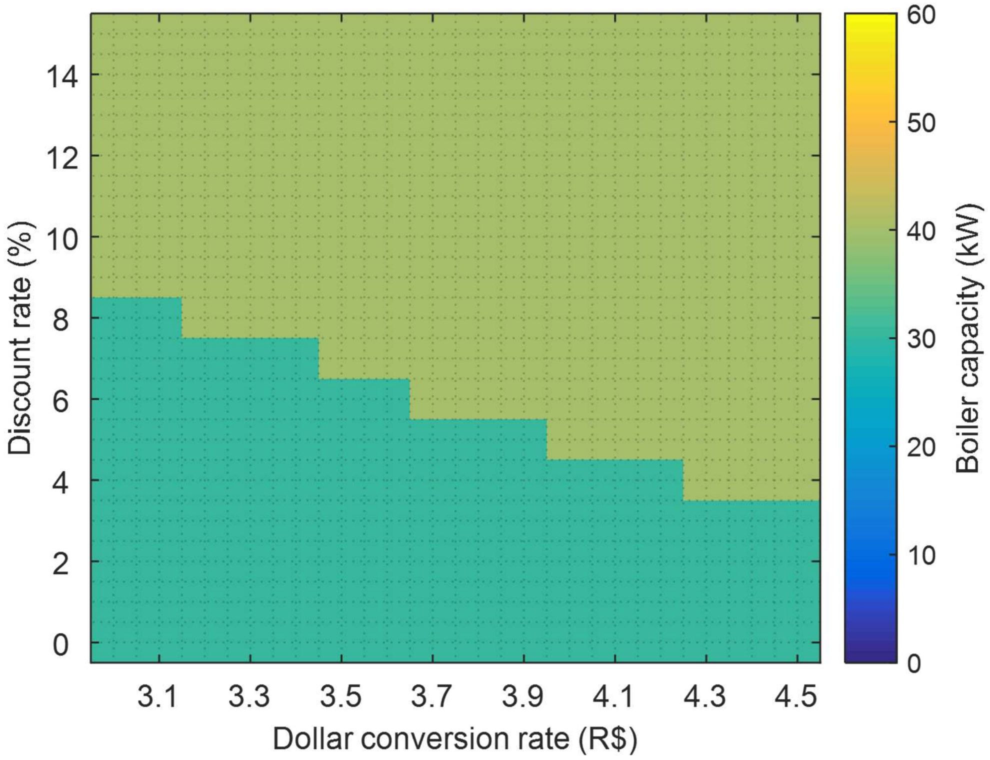
In the sequence, the prime mover sizing (electrical) and boiler sizing to the postgraduate case with equipment taxes are presented in Figure 44 and Figure 45, respectively. The same behaviour observed on the prime mover and boiler sizing without equipment taxes is noted this time. The only difference is that the decision of no investment on trigeneration systems is present when taxes are considered. Consequently, the prime mover size can range from 0kW to 10kW, and the boiler size is still varying from 30kW to 40kW.

Figure 44 – Sizing of the prime mover (electrical) at maximum net present values to the postgraduate building case with equipment taxes



Source: Author

Figure 45 – Sizing of the boiler at maximum net present values to the postgraduate building case with equipment taxes



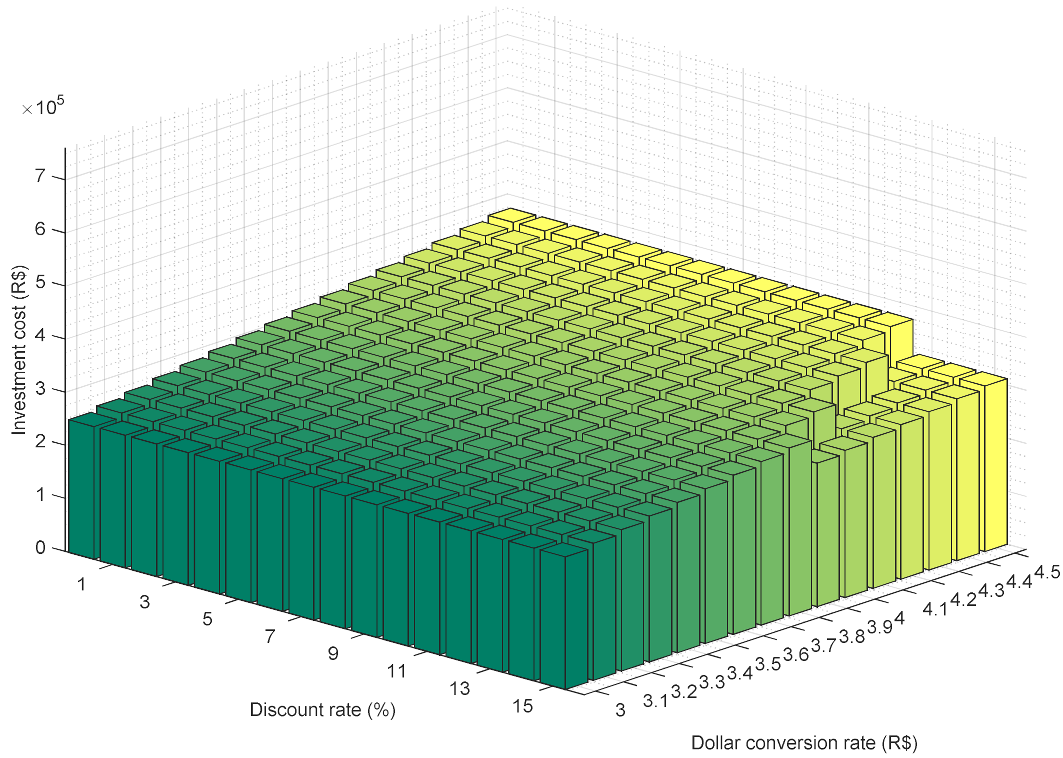
Source: Author

From the prime mover and boiler sizing, together with the absorption chiller size, it is possible to obtain the equipment investment cost. So, it is shown in Figure 46 the investment cost without taxes and in Figure 47 the same cost considering taxes. The average investment cost without taxes is around R$ 309 thousand, while the taxes rise the average investment cost to around R$ 544 thousand.

Figure 48 shows the grid dependence index of the building at maximum net present values without equipment taxes. In general, the GDI is very low, 100% of situations are below 12% of dependence from the external grid. As can be seen in this simulation, the optimisation indicates that the trigeneration system should work with minimum power from the external network.

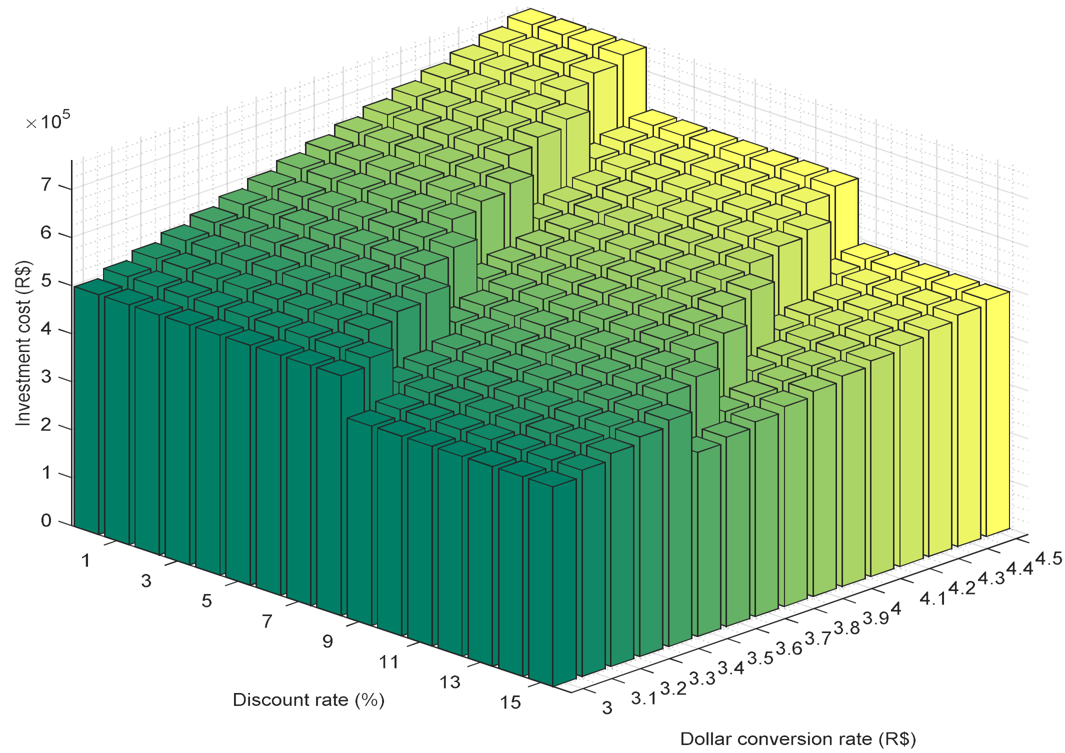
Now, Figure 49 shows the result of grid dependence index for the building at maximum net present values with equipment taxes. At this time, the GDI is still very low to more than 85% of situations, which are below 12%. However, as the discount rate gets higher, GDI goes to its maximum values, around 42%. When the GDI achieves 42%, it means that the prime mover sizing is zero, in other words, the optimisation process decides for non-installation of a trigeneration system. As a consequence, only the boiler and absorption chiller are installed.

Figure 46 – Variation on investment cost at maximum net present values to the postgraduate building case without equipment taxes



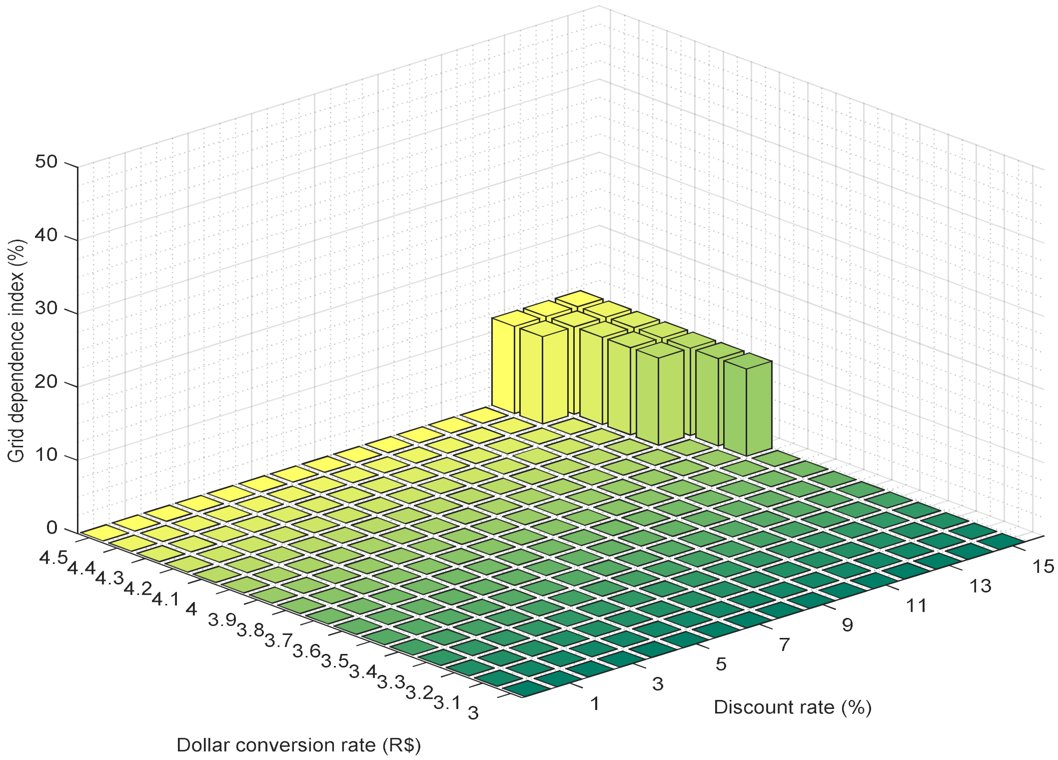
Source: Author

Figure 47 – Variation on investment cost at maximum net present values to the postgraduate building case with equipment taxes



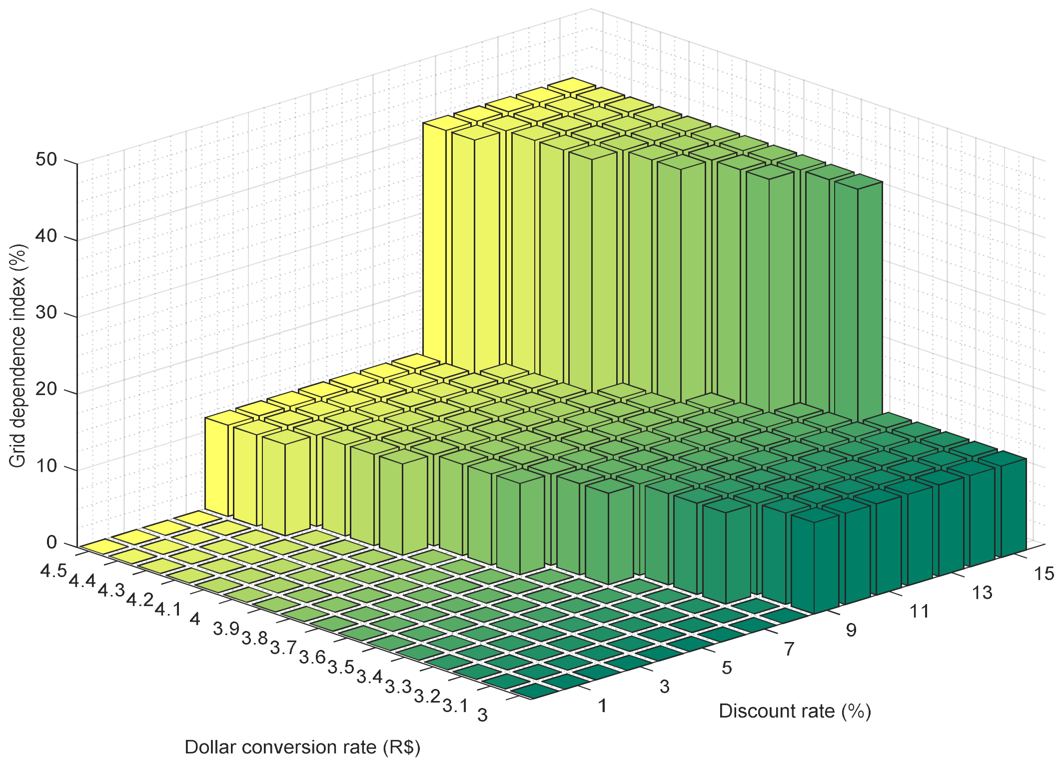
Source: Author

Figure 48 – Variation on grid dependence index at maximum net present values to the postgraduate building case without equipment taxes



Source: Author

Figure 49 – Variation on grid dependence index at maximum net present values to the postgraduate building case with equipment taxes



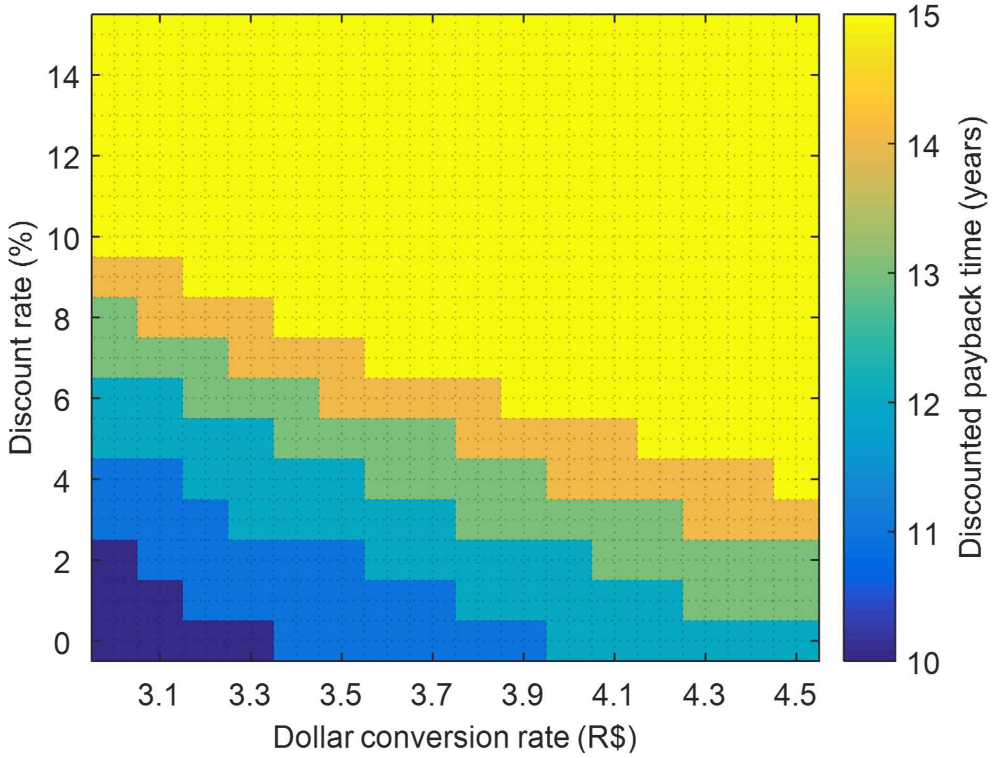
Source: Author

Analysing and comparing the two GDIs sensitivity studies, it is possible to observe that in the simulation without taxes the grid dependence is low in all economic situation, so the CCHP system is responsible to supply most of the energy load. In the simulation considering taxes, although, the trigeneration system sizing and operation depend on the economic scenario, and in some cases the trigeneration system is not profitable.

The discounted payback time without equipment taxes is presented in Figure 50. As it can be seen, the minimum discounted payback time is 10 years, which is not an encouraging result. But as the building is not for profit, the investment could be a possibility if the installed system was used for research purposes. It is important to clarify that results represented as 15 years of payback, in this study, can be higher or equal to 15 years, anyway, those results are not interesting to investors.

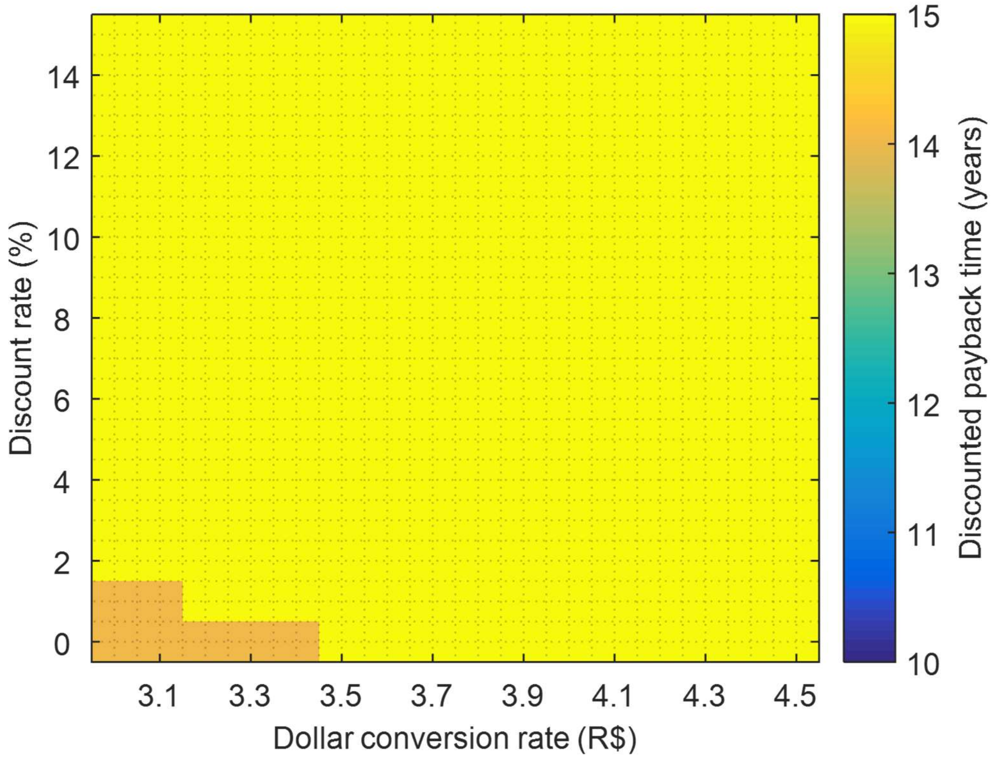
Figure 51 shows the discounted payback time with equipment taxes. In this case, all the situations are not financially beneficial. As the situations have discounted payback time equal or higher than 14 years, it is just in the limit of the system lifespan. However, if the system was installed with research purposes, it would be beneficial to postgraduate researches executed in the energy area.

Figure 50 – Variation on discounted payback at maximum net present values to the postgraduate building case without equipment taxes



Source: Author

Figure 51 – Variation on discounted payback at maximum net present values to the postgraduate building case with equipment taxes

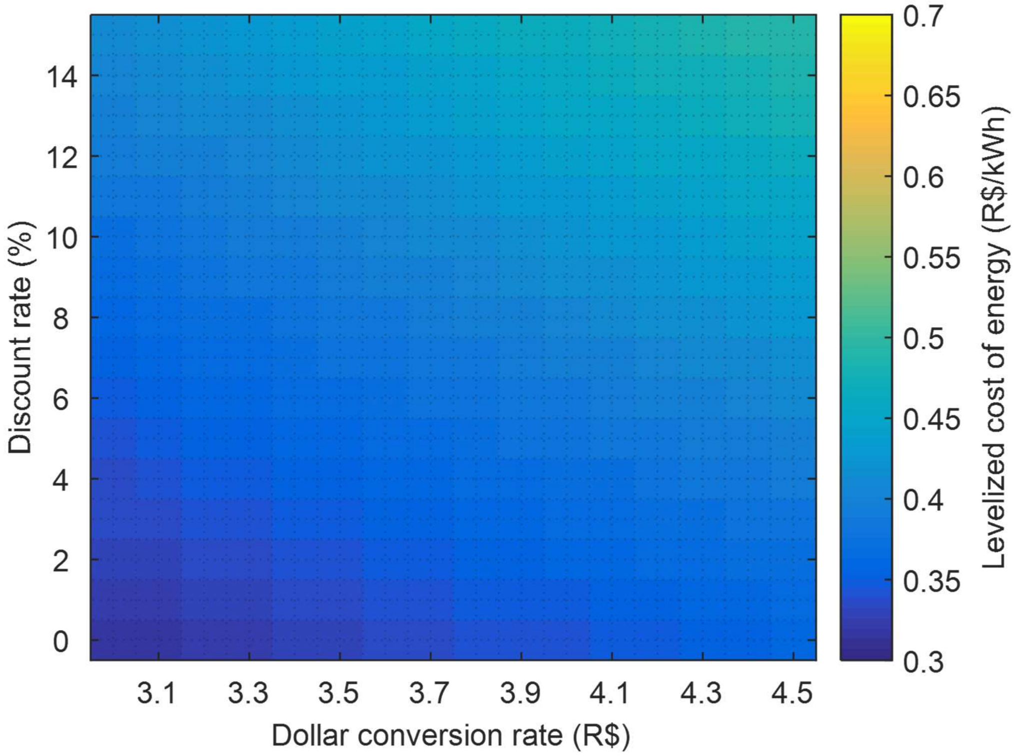


Source: Author

This time, the levelized cost of energy values without taxes and with taxes are presented in Figure 52 and Figure 53, respectively. The LCOE without taxes ranges from around 0.32 R$/kWh to around 0.49 R$/kWh with an average of 0.39 R$/kWh, while the LCOE considering taxes varies from around 0.38 R$/kWh to around 0.67 R$/kWh with an average of 0.51 R$/kWh. As a conclusion, the LCOE is influenced by variation in discount rates, US Dollar conversion rates and the taxes, in other words, financial benefits diminish when the complete system price gets higher.

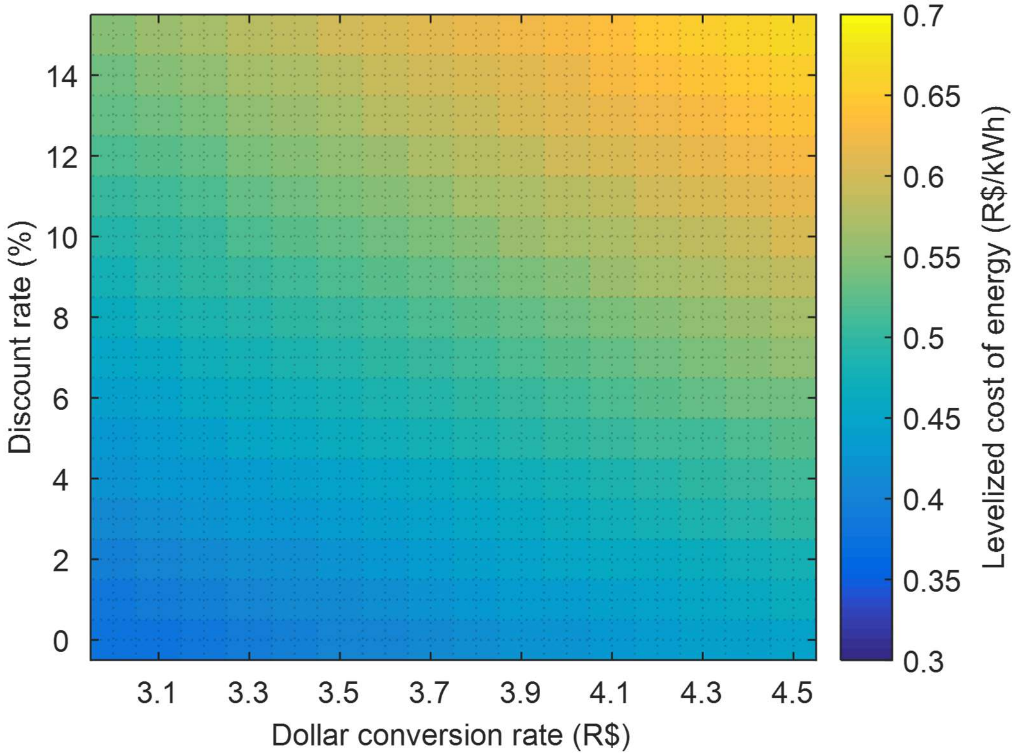
Lastly, the primary energy ratios without taxes are showed in Figure 54 and with taxes in Figure 55. The PER without taxes goes from about 0.67 to about 0.68 with an average of 0.68, while the PER with taxes goes from about 0.65 to about 0.68 with an average of 0.67. As can be seen, the efficiency does not vary considerably, so there are few influences of discount rates, US Dollar conversion rates and taxes on PER results.

Figure 52 – Variation on levelized cost of energy at maximum net present values to the postgraduate building case without equipment taxes



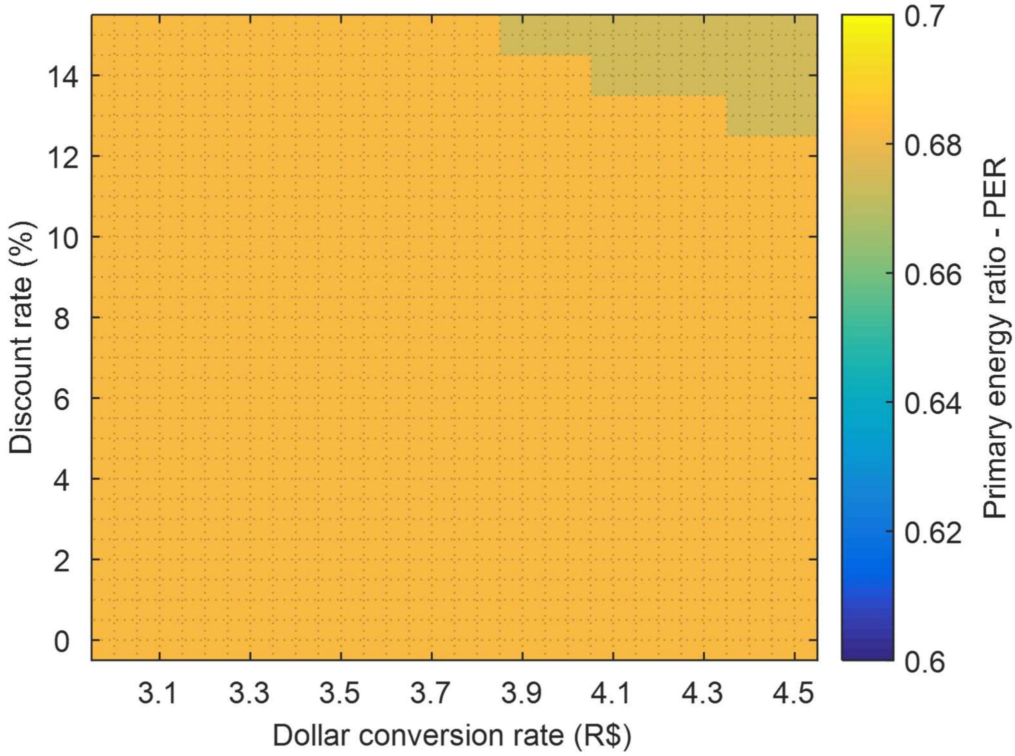
Source: Author

Figure 53 – Variation on levelized cost of energy at maximum net present values to the postgraduate building case with equipment taxes



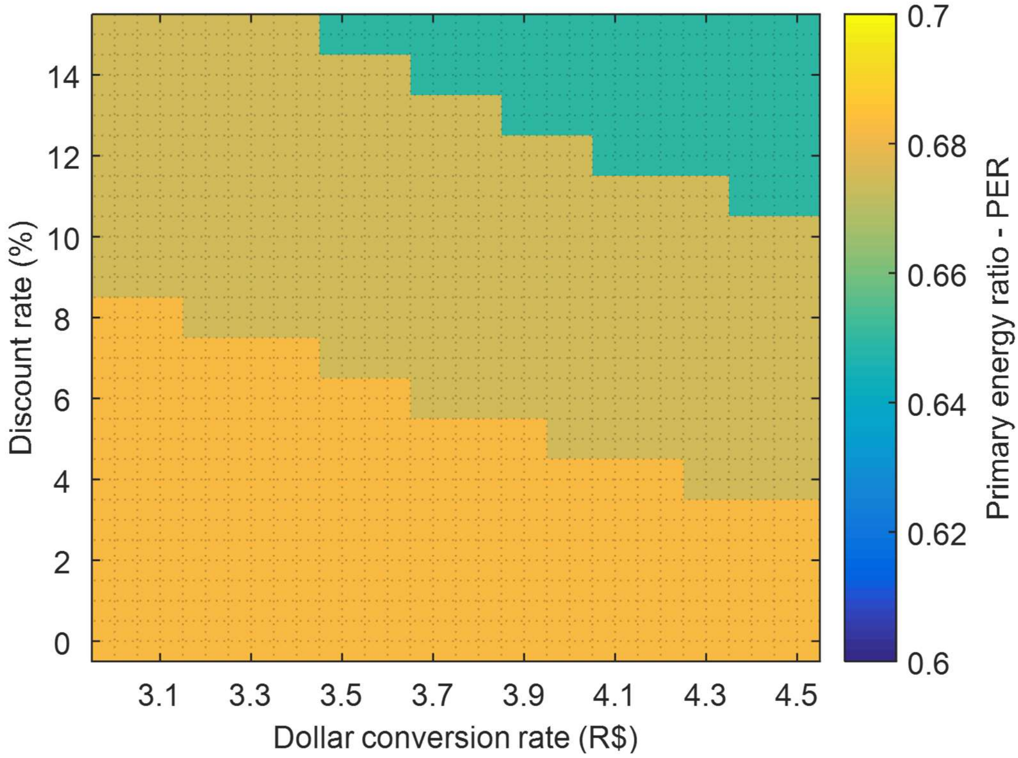
Source: Author

Figure 54 – Variation on primary energy ratio at maximum net present values to the postgraduate building case without equipment taxes



Source: Author

Figure 55 – Variation on primary energy ratio at maximum net present values to the postgraduate building case with equipment taxes



Source: Author

In summary, the presented study case 3 shows that trigeneration systems to federal postgraduate buildings are hardly profitable in Brazil. Also, each case has different results, so another research building with higher energy demand, or in non-federal universities, can show itself more suitable to trigeneration systems than others. Moreover, if considered the use of national equipment to the system, the financial benefits would probably increase. Additionally, this work gives parameters to investors decide if Brazilian federal university buildings have potential to trigeneration systems, as each sector has its own economical indexes and necessities, they can use the sensitivity study to have an idea of profitability or suitability. Obviously a more detailed study has to be made, in order to have a real picture of financial and research benefits. In this study case, the possibility of research using the proposed trigeneration system could make the investment a good option, because considering the electric and energy point of view the system is a good opportunity to develop researches.

3.5 CASE STUDY 4

The fourth discussed case is a hotel building hypothetically located in Juiz de Fora, Minas Gerais, and connected to the medium voltage network. The tariff policy used by the building is also the A4 green tariff, which has one fixed demand price and the electric energy price is time of use based [42]. Moreover, all the tariffs are already with taxes (ICMS, PASEP and COFINS), and it is used the green flag in this study. The demand and electricity tariffs, and taxes used on this work are presented on Table 11 and they are from June, 2018 [32,43].

Table 11 – Demand and electricity tariffs, and taxes to study case 4

Taxes names	**ICMS**	**PASEP**	**COFINS**
Taxes (%)	25	0.56	1.90
Time of use periods	**From 0h to 18h**	**From 18h to 21h**	**From 21h to 0h**
Electricity tariff price – first year (R$/kWh)	0.4450	2.1276	0.4450
Demand price (R$/kW)	20.1130	20.1130	20.1130

Source: Companhia Energética de Minas Gerais - CEMIG, 2018

The natural gas tariff used by the hotel is the cogeneration tariff, which has a fixed and a variable tariff. Moreover, all the tariffs are already with taxes (ICMS, PASEP and COFINS) and the variable tariff was converted to R$/kWh, as already explained. The fixed and variable natural gas tariffs with taxes, and the applied taxes percentage used on this work are presented in Table 12 (they are from June, 2018) [44].

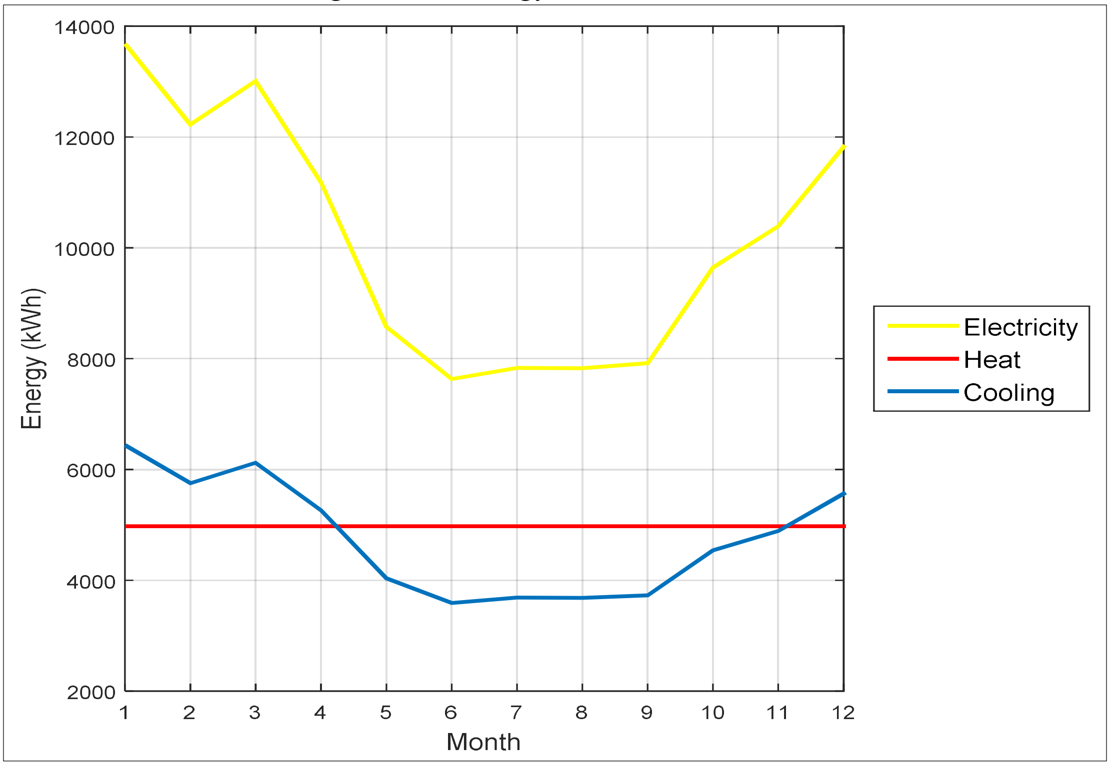
Table 12 – Fixed and variable natural gas tariffs, and taxes percentage to study case 4

Taxes names	**ICMS**	**PASEP**	**COFINS**
Taxes (%)	12	1.65	7.60
Tariffs		**Value**	
Natural gas tariff (R$/kWh)		0.18596	
Fixed natural gas tariff (R$)		99.69	

Source: Companhia de Gás de Minas Gerais - GASMIG, 2018

Furthermore, the energy demand data is from a Brazilian hotel [46]. The data was processed according to the document description, and it was adapted to the input format used in this thesis. The processed energy demand is shown in Figure 56. Although it is not from Minas Gerais, it still represents the Brazilian weather and consumption characteristics. This is also the reason of calling the hotel as having a hypothetical location, because it is based on real data from Brazil but it is not from the same location where it was placed in this study case.

Figure 56 – Energy demand at the hotel



Source: Author

3.5.1 The Reference Case to the Study Case 4

As the reference case is electricity-based, the three energy demands (electricity, heating and cooling) of the hotel are summed into one electric load, always considering electric boiler and chiller efficiencies. Then, the electric energy tariff is applied over the consumed electricity to each month, and the demand tariff is applied to the maximum demand of each month. It is important to clarify that green tariff prices to commercial buildings are applied (Table 11), and also it is considered annual readjustment on the electricity price. The simulation is done according to the next section procedure.

3.5.2 The Detailed Optimisation Process to the Study Case 4

The first consideration about this case is that the considered lifespan of the system is 15 years, so to each simulation the number of calculated years will be limited to this value. Moreover, the discount rate (*discount_rate*) is varied from 0% to 30% in 2% steps, as well as, the US Dollar to Brazilian Real conversion price (*dollar*) is varied from R$3.00 to R$4.50 in R$0.10 steps. Equally important is the variation of the prime mover electric generation capacity (*Cpm*), from 0kW to 20kW in 5kW steps, and the boiler heat generation capacity (*boiler*), from 0kW to 40kW in 10kW steps.

Considering the given information about study case 4, it is possible to set the variables present on the flowchart explained in Figure 4. So, Table 13 shows the optimization flowchart variable values to study case 4.

Table 13 – Optimization flowchart variable values to study case 4

Variable	Value
ddiscount_rate	2%
mdiscount_rate	30%
dCpm	5 kW
mCpm	20 kW
dcboiler	10 kW
mboiler	40 kW

Source: Author

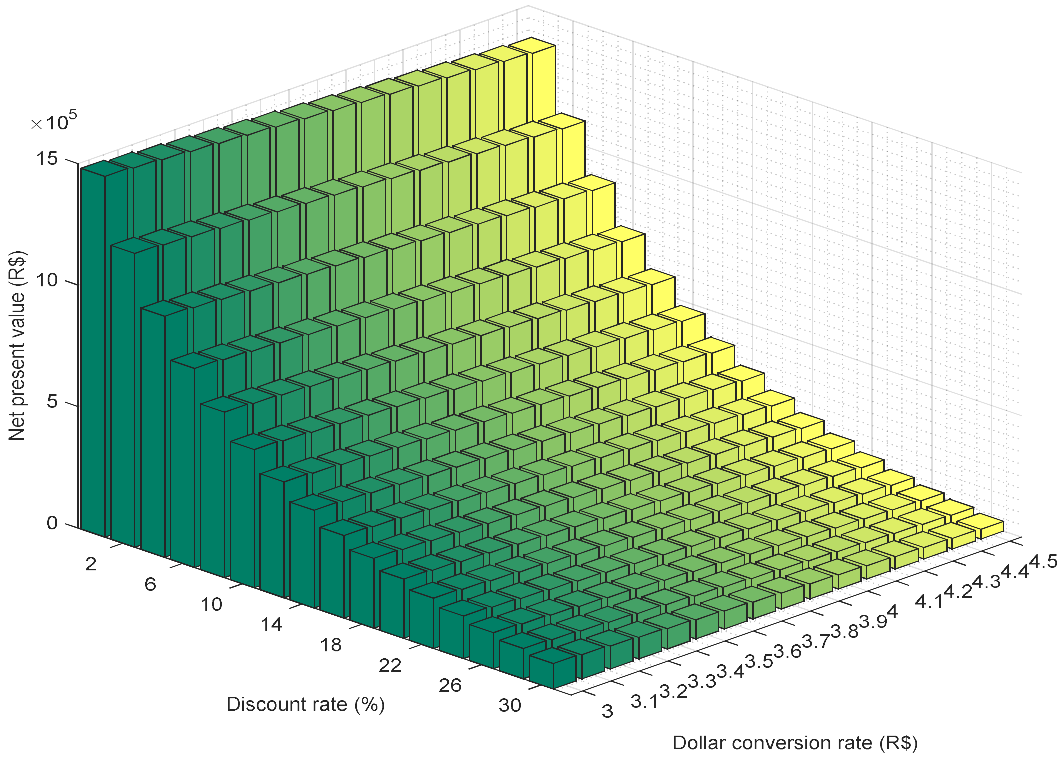
3.5.3 Results and Analysis to the Study Case 4

This section will present simulation results from the study case 4. In the first place, it will be presented the net present value sensitivity study, and then, the equivalent equipment sizing, the investment cost, the equivalent grid dependence index, the discounted payback time, the levelized cost of energy and the primary energy ratio. All of them are simulated, firstly, without equipment taxes, and then, considering equipment taxes.

The first result to be presented and analysed is the net present value sensitivity study without equipment taxes. As it can be seen on Figure 57, the net present value decreases as the discount rate and US Dollar conversion rate increase. Also, the impact of rate variation on the

NPV is higher with discount rate than with US Dollar. In general, the NPV is higher than zero in all the situations of discount rate and considered US Dollar conversion rate variation, so the investment is entirely safe from the NPV point of view. However, the investment return depends on the chosen discount rate and actual US Dollar conversion rate.

Figure 57 – Maximum net present values to the hotel case study without equipment taxes

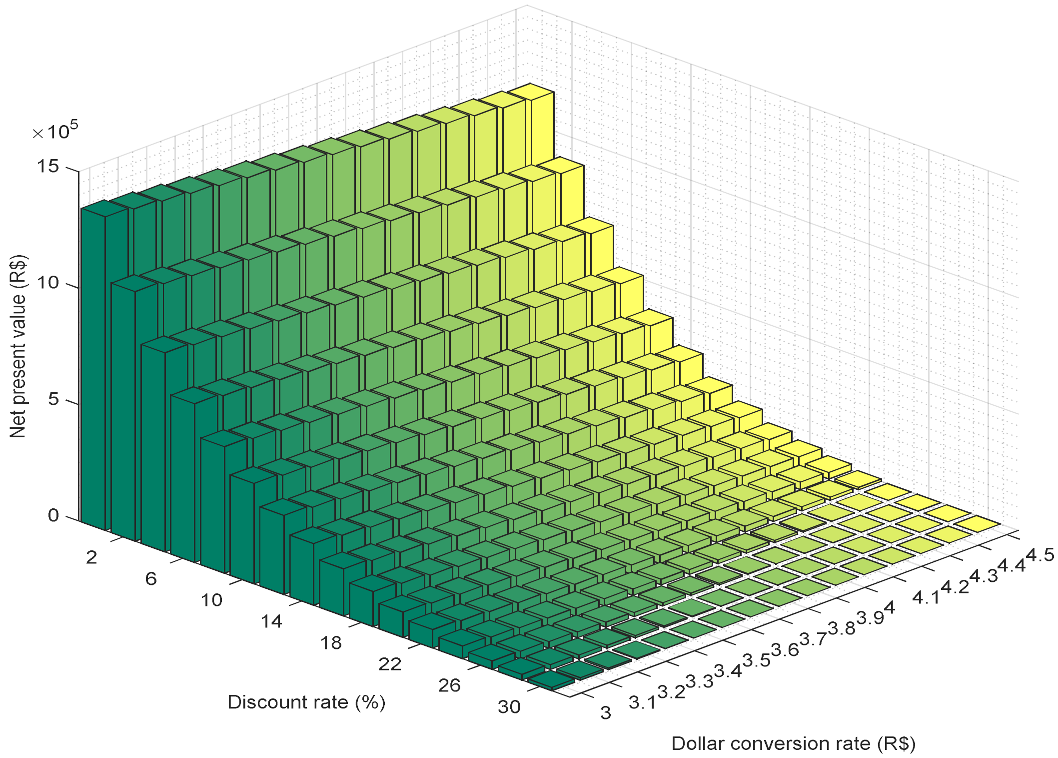


Source: Author

The second result to be presented is the net present value sensitivity study with equipment taxes. As it can be seen in Figure 58, the net present value also decreases as the discount rate and US Dollar conversion rate increase, as expected. Moreover, the impact of rate variation on the NPV is also higher with discount rate than with US Dollar. In general, the NPV is higher than zero from 0% to 22% of discount rate and to any considered US Dollar conversion rate variation, so this is the safest region to investment as the US Dollar variation does not strongly affect the investment return. However, from 24% to 30% of discount rate, the positive NPV depends on the US Dollar conversion rate, therefore this region is riskier than the previous one.

Comparing the previous presented net present values sensitivity studies, the only input difference is on the machinery investment price. In the first situation, taxes imposed by the Brazilian government are ignored, consequently, the NPV is higher than in the second situation, which considers maximum estimated taxes (100%). Again, from the previous presented situations, it can be concluded that Brazilian taxes limit the investment return on trigeneration systems.

Figure 58 – Maximum net present values to the hotel case study with equipment taxes

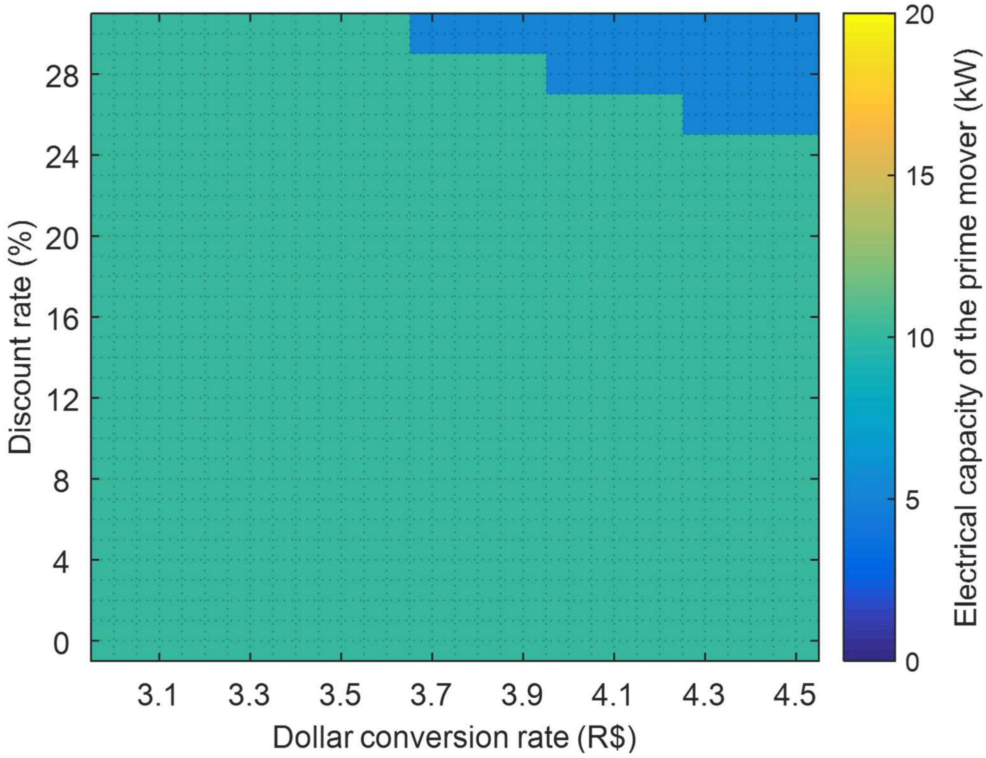


Source: Author

After the decision of the highest available NPV, it is possible to find specific size of the three components of the trigeneration system, the investment cost, the grid dependence index, the payback time, the levelized cost of energy, and the primary energy ratio related to the maximum NPVs. Therefore, the prime mover sizing (electrical) and boiler sizing to the hotel case without equipment taxes are presented in Figure 59 and Figure 60, respectively. Also, the absorption chiller size corresponds to the maximum cooling demand of the building, as it is not optimised there is no sizing study to absorption chillers on this work.

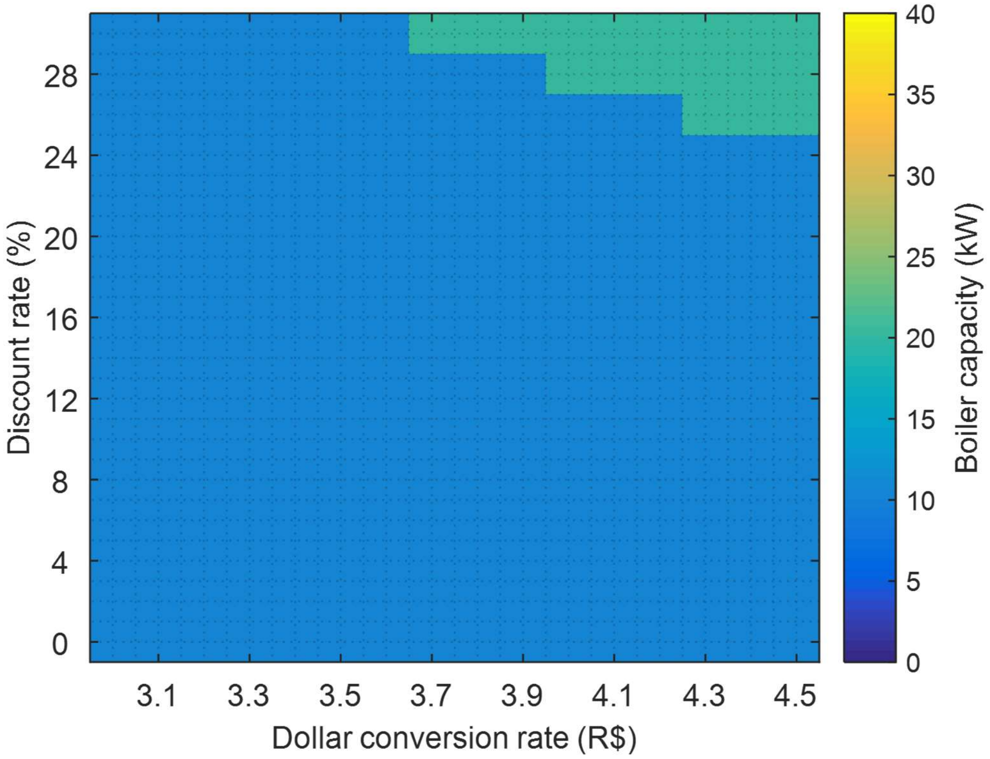
In general, the prime mover capacity decreases as the discount rate and US Dollar conversion rate increases, thus, the prime mover size can go from 5kW to 10kW. In contrast, the boiler size capacity increases as the discount rate and US Dollar conversion rate increases, and its capacity can range from 10kW to 20kW. Once more, if a comparison is made between the prime mover and boiler sizing capacities, it is possible to conclude that the prime mover size is complementary to the boiler size.

Figure 59 – Sizing of the prime mover (electrical) at maximum net present value to the hotel case without equipment taxes



Source: Author

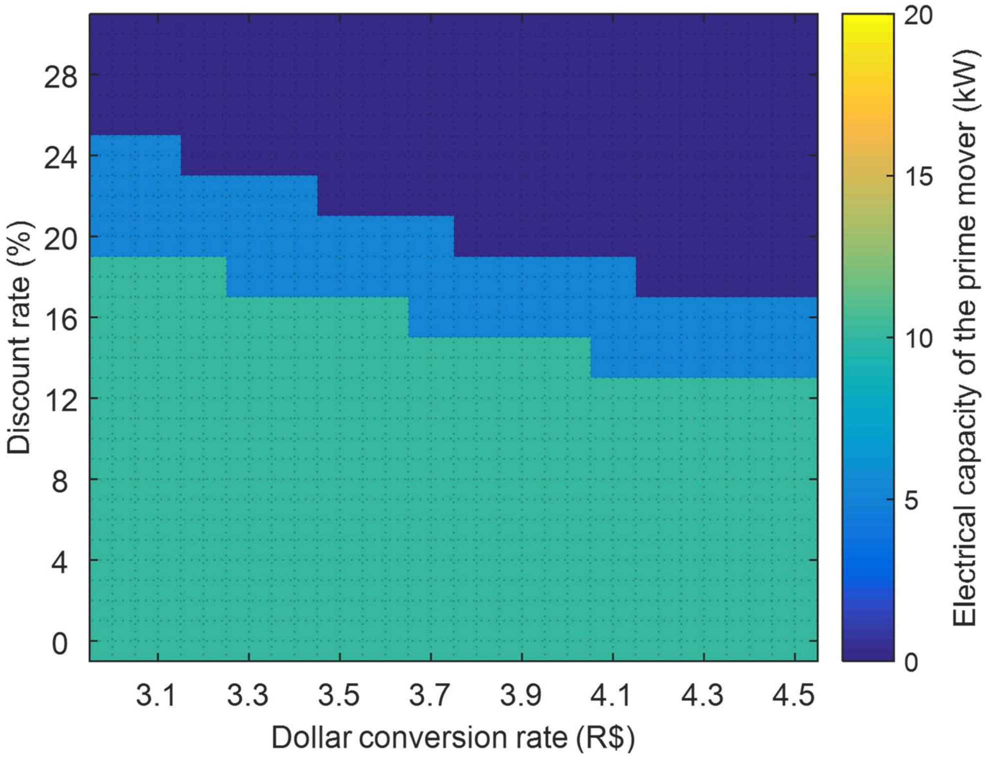
Figure 60 – Sizing of the boiler at maximum net present value to the hotel case without equipment taxes



Source: Author

In the sequence, the prime mover sizing (electrical) and boiler sizing to the hotel case with equipment taxes are presented in Figure 61 and Figure 62, respectively. The same behaviour observed on the prime mover and boiler sizing without equipment taxes is noted this time. The only difference is that the decision of no investment on trigeneration systems is a reality in some situations.

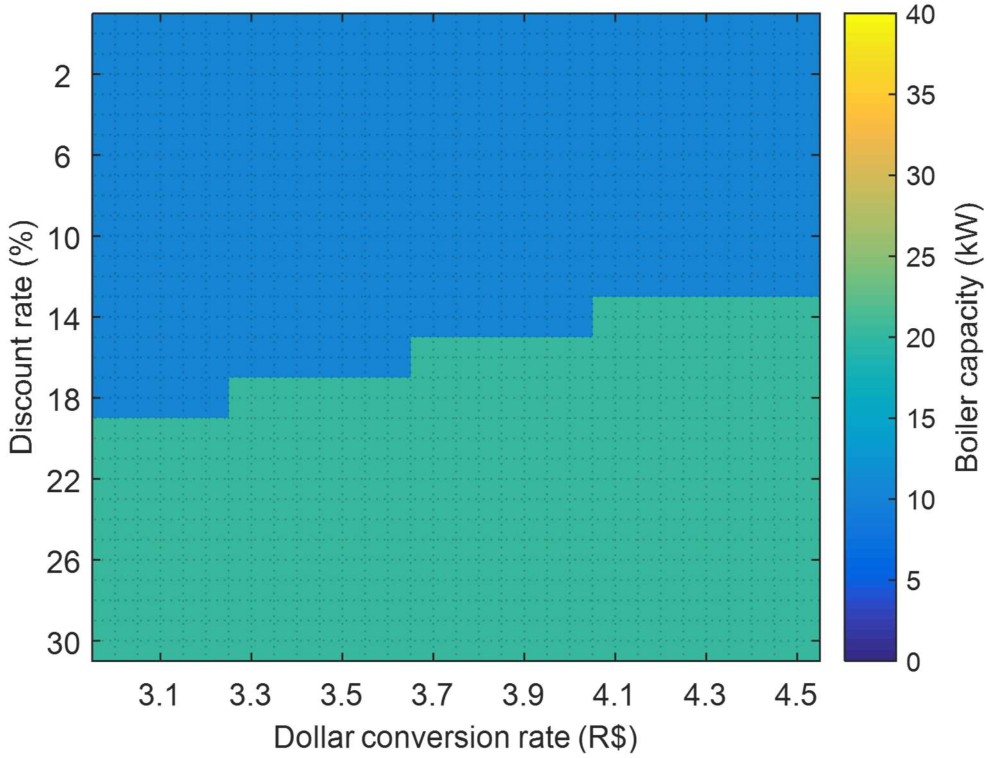
Figure 61 – Sizing of the prime mover (electrical) at maximum net present value to the hotel case with equipment taxes



Source: Author

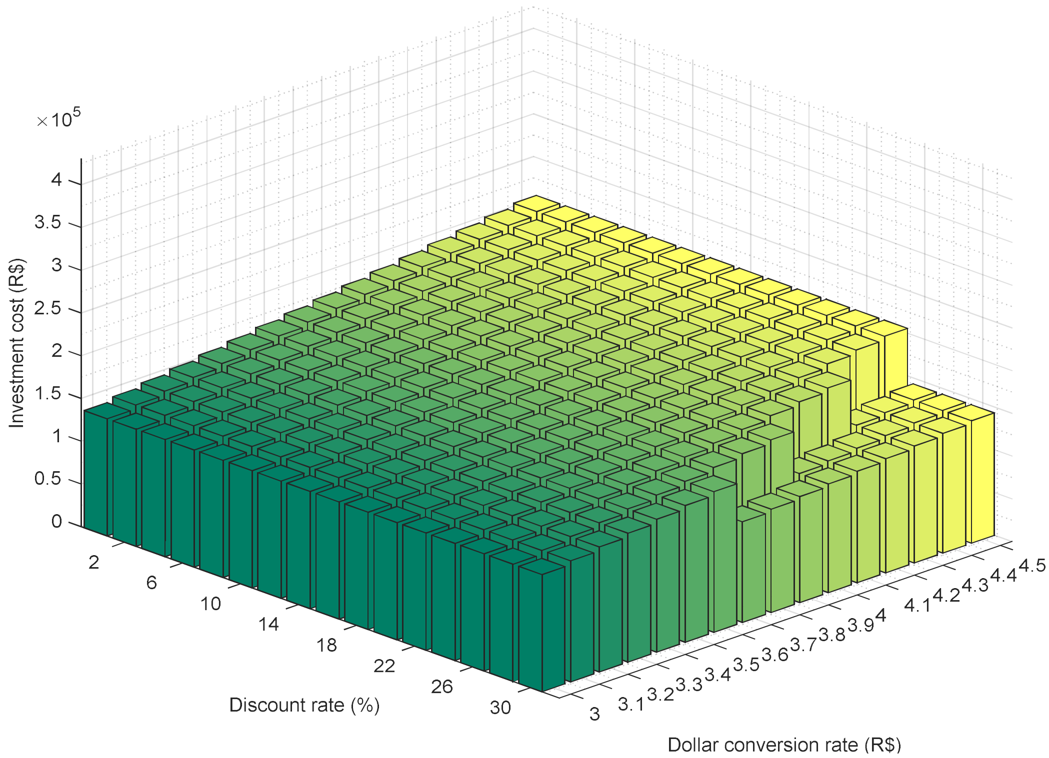
From the prime mover and boiler sizing, together with the absorption chiller size, it is possible to obtain the equipment investment cost. So, it is shown in Figure 63 the investment cost without taxes and in Figure 64 the same cost considering taxes. The average investment cost without taxes is around R$ 167 thousand, while the taxes rise the average investment cost to around R$ 254 thousand.

Figure 62 – Sizing of the boiler at maximum net present value to the hotel case with equipment taxes



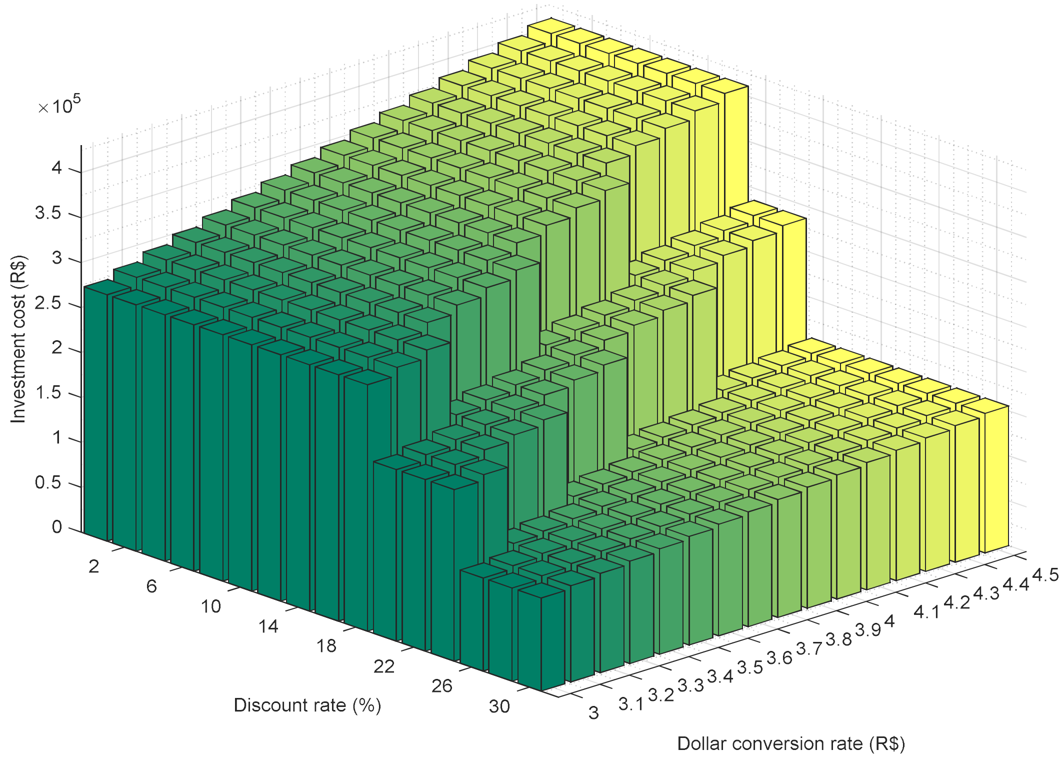
Source: Author

Figure 63 – Variation on investment cost at maximum net present values to the hotel case without equipment taxes



Source: Author

Figure 64 – Variation on investment cost at maximum net present values to the hotel case with equipment taxes



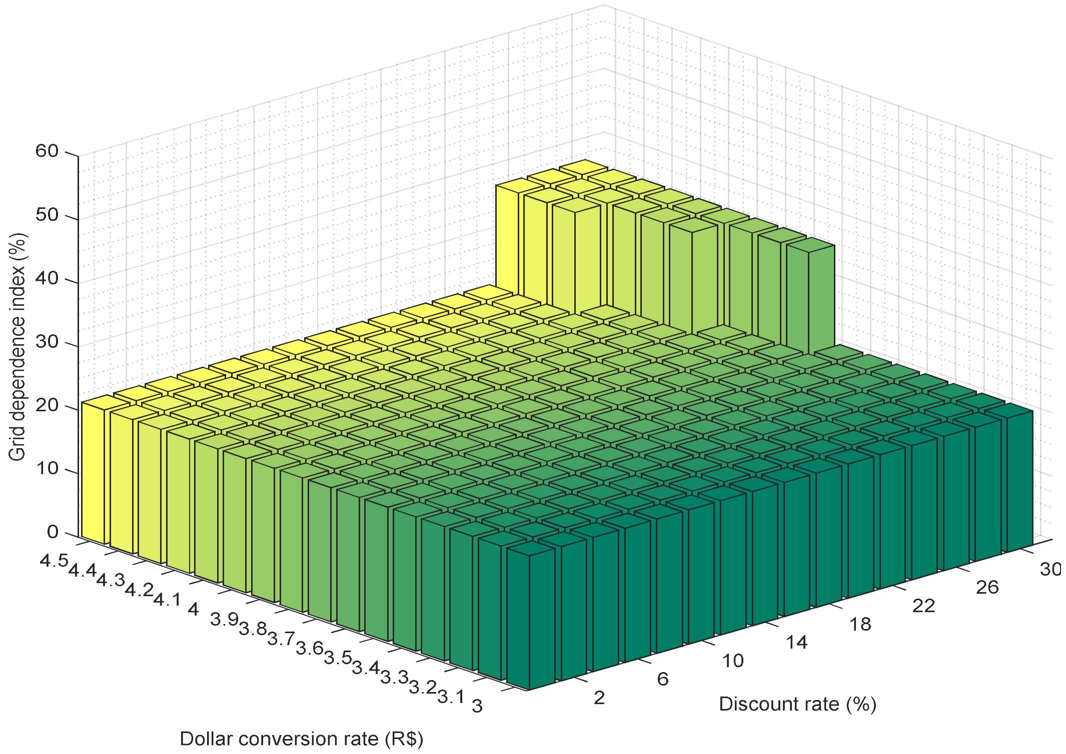
Source: Author

Figure 65 shows the grid dependence index of the building at maximum net present values without equipment taxes. The GDI is low, it has more than 90% of situations below one quarter of dependence from the external grid. However, when the discount rate is between 26% and 30% and for specific high US Dollar conversion rates, the GDI gets at its maximum value, around 36%. As can be seen, for this simulation, the optimisation indicates that the trigeneration system should work with minimum power from the external network.

Figure 66 shows the result of grid dependence index for the building at maximum net present values with equipment taxes. At this time, the GDI is still low to around half of situations, which are below 25%. However, as the discount rate gets higher, GDI goes to its maximum values, around 57%. When this occur, it means that the prime mover sizing is zero, in other words, the optimisation process decides for non-installation of a trigeneration system. As a consequence, only the boiler and absorption chiller are installed.

Analysing and comparing the two GDIs sensitivity studies, it is possible to observe that in the simulation without taxes the grid dependence is low in almost all economic situation, so the CCHP system is responsible to supply most of the energy load. In the simulation considering taxes, although, the trigeneration system sizing and operation depend on the economic scenario, and in some cases the trigeneration system is not profitable.

Figure 65 – Variation on grid dependence index at maximum net present values to the hotel case without equipment taxes

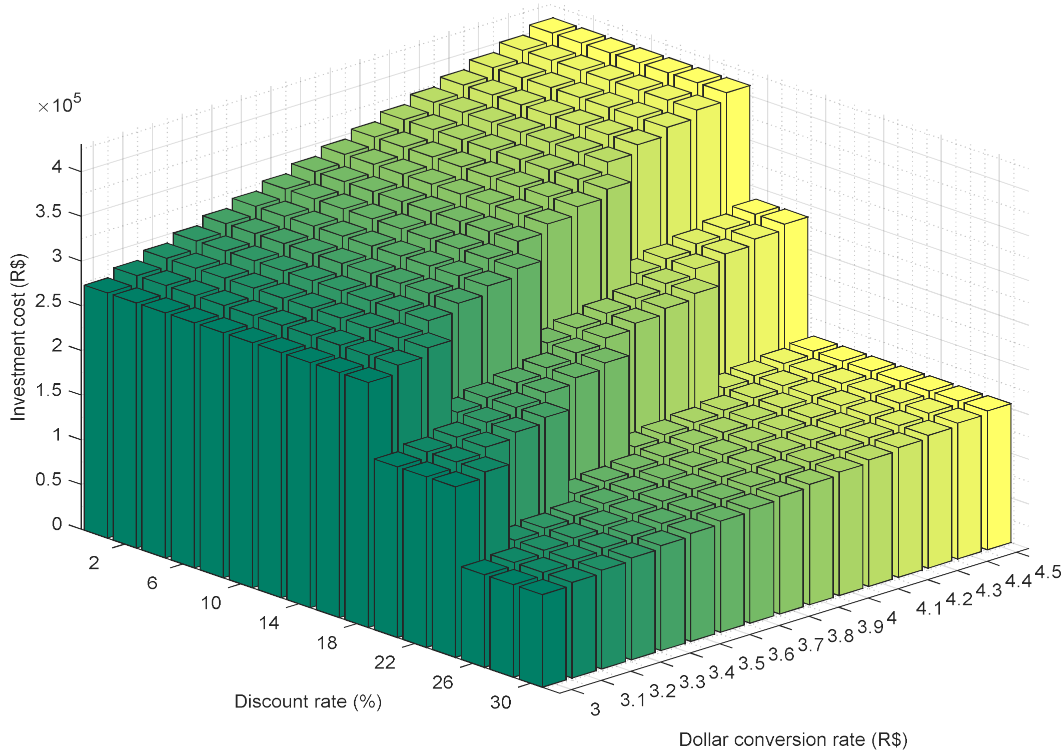


Source: Author

The next presented result is the discounted payback time without equipment taxes, Figure 67. As it can be seen, the minimum discounted payback time is 3 years, which is a considerably good result, but the discount rate to this payback time is still low to a business. Again, results represented as 15 years of payback, in this study, can be higher or equal to 15 years, anyway, those results are not interesting to investors. In the rest of the situations, there are payback times from 4 to 8 years, which could attract the attention of investor.

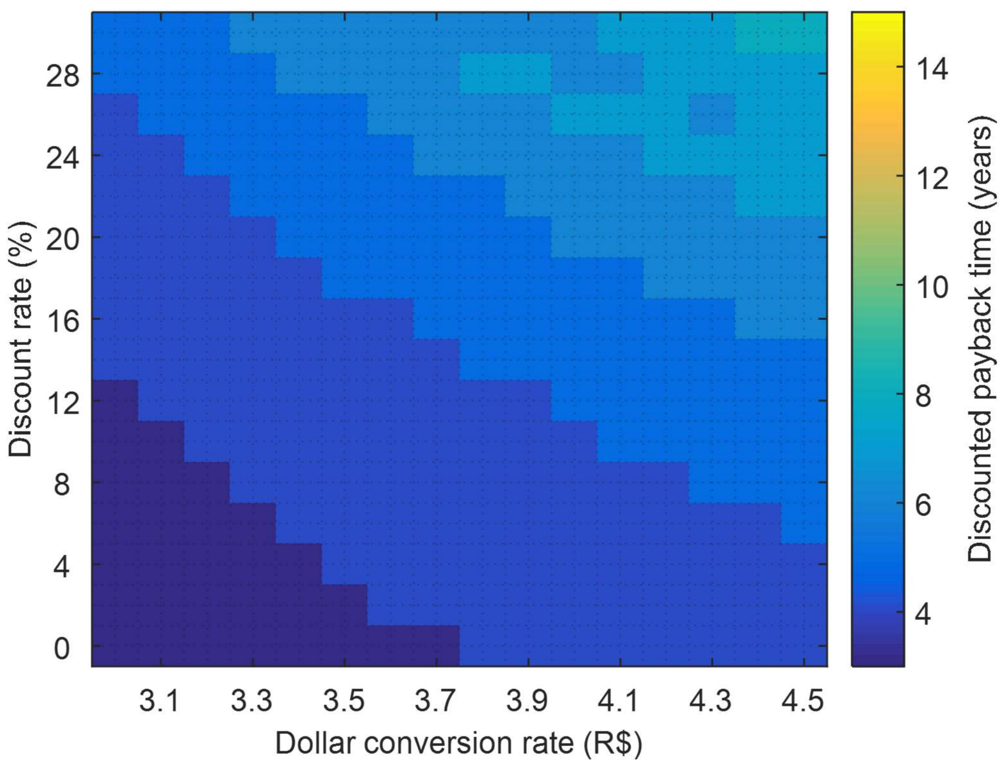
Figure 68 shows the discounted payback time with equipment taxes. In this case, the minimum discounted payback time is 5 years, which is not a bad result, but the respective discount rate is still low to a business. In the middle, there are payback times from 6 to 10 years, which could attract attention of few investor, maybe none. The rest of the situations have payback time higher than 10 years, which probably cannot attract investors attention.

Figure 66 – Variation on grid dependence index at maximum net present values to the hotel case with equipment taxes



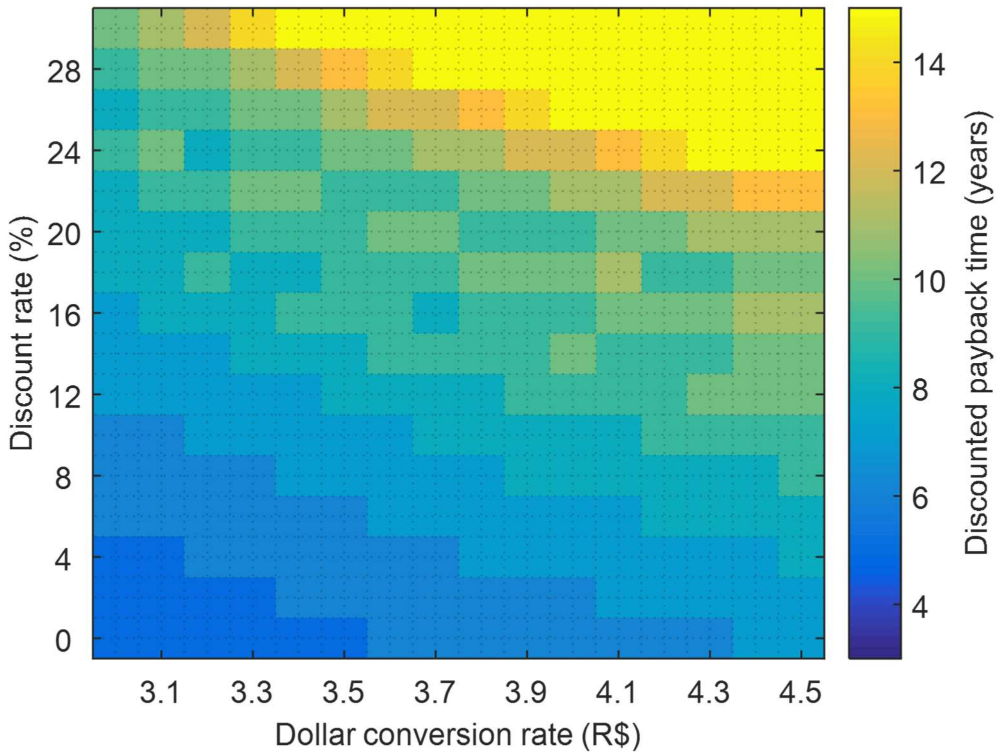
Source: Author

Figure 67 – Variation on discounted payback at maximum net present values to the hotel case without equipment taxes



Source: Author

Figure 68 – Variation on discounted payback at maximum net present values to the hotel case with equipment taxes

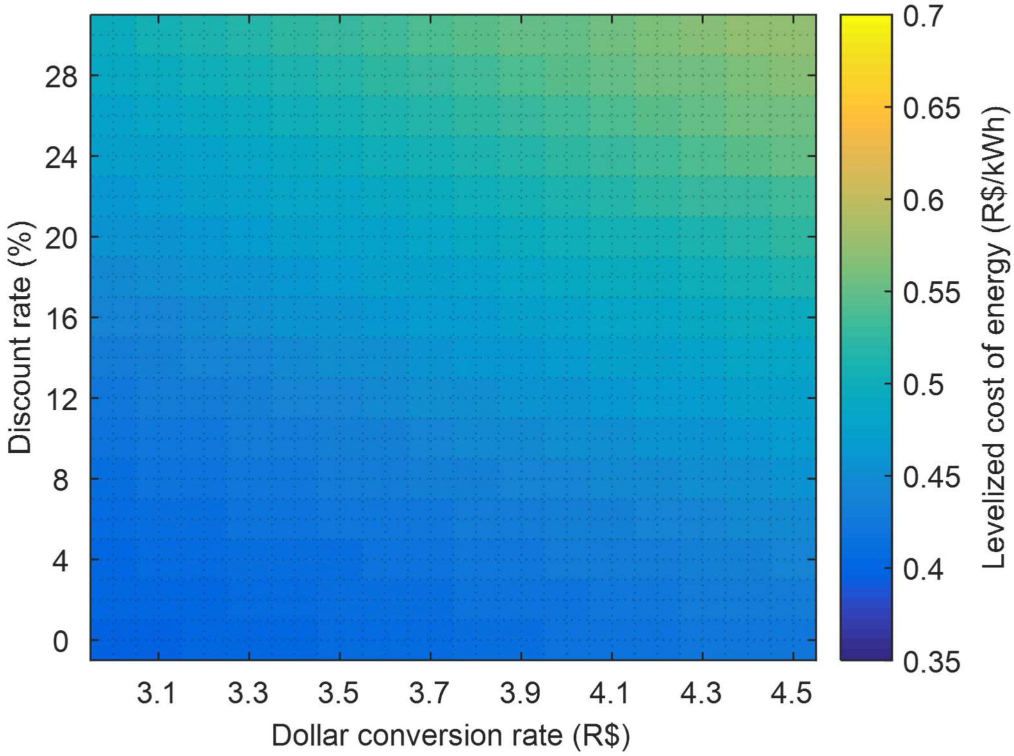


Source: Author

The last study case has a levelized cost of energy that ranges from approximate 0.40 R$/kWh to approximate 0.57 R$/kWh with an approximate average of 0.47 R$/kWh when taxes are not considered, Figure 69. While the LCOE with taxes ranges from around 0.43 R$/kWh to around 0.67 R$/kWh with an approximate average of 0.56 R$/kWh, Figure 70. Then, there is a clear increase on the LCOE value when compared the scenario without taxes to the scenario with taxes, as expected.

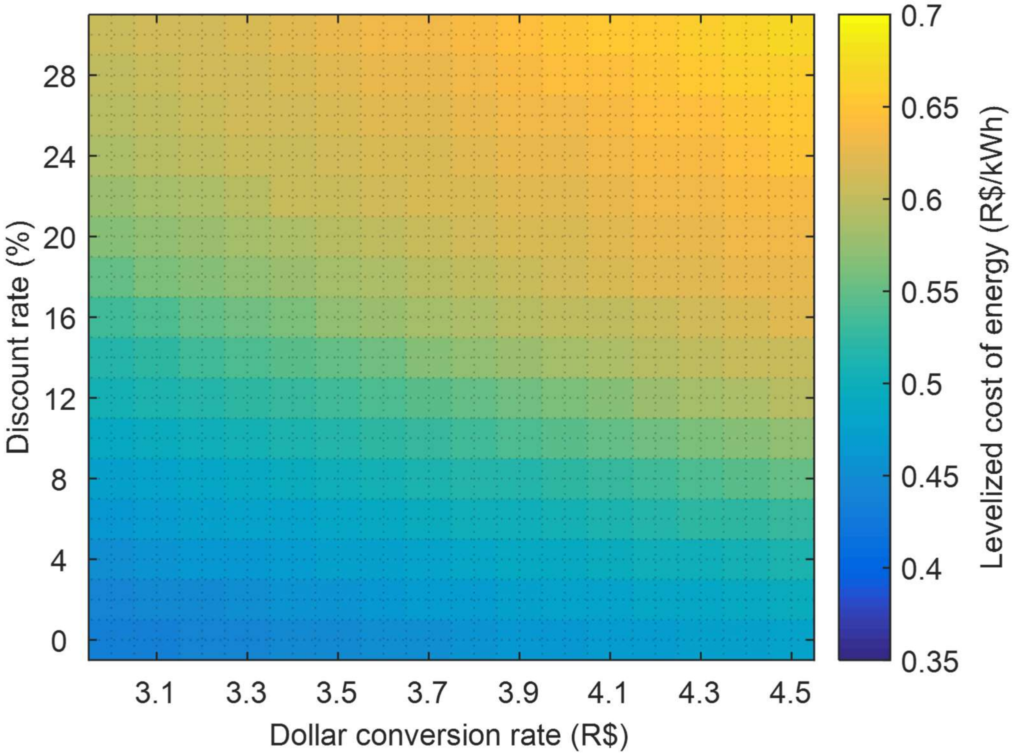
The primary energy ratio without taxes is shown in Figure 71, so it varies from around 0.73 to around 0.74 with an approximate average of 0.74. Also, the PER with taxes are shown in Figure 72. Then it ranges from about 0.71 to about 0.74 with an approximate average of 0.73. Once more, the variation is not severe influenced by the price changes and the average primary energy conversion efficiency is considerably high, which proves the energetic benefit of using trigeneration systems instead of traditional ones.

Figure 69 – Variation on levelized cost of energy at maximum net present values to the hotel case without equipment taxes



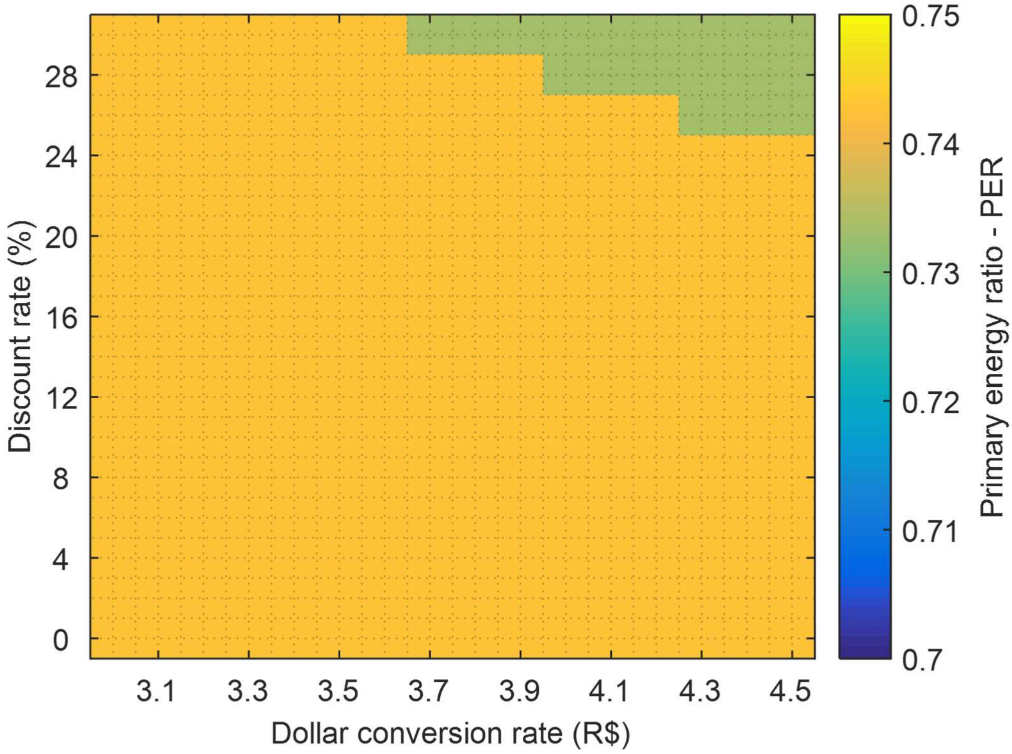
Source: Author

Figure 70 – Variation on levelized cost of energy at maximum net present values to the hotel case with equipment taxes



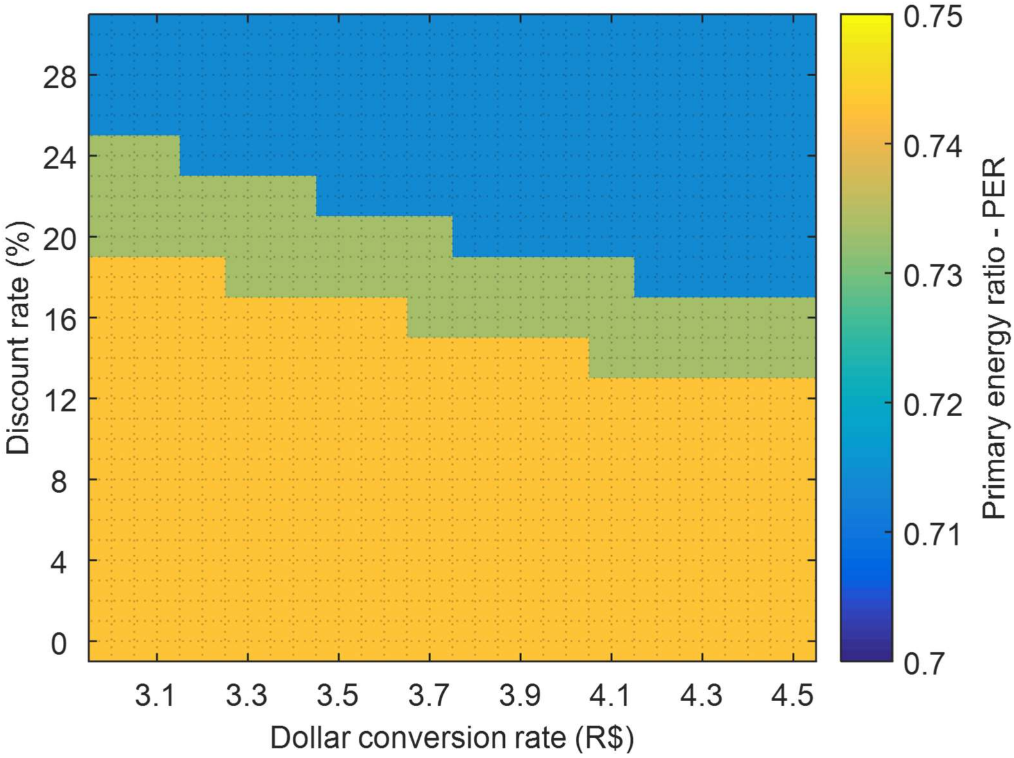
Source: Author

Figure 71 – Variation on primary energy ratio at maximum net present values to the hotel case without equipment taxes



Source: Author

Figure 72 – Variation on primary energy ratio at maximum net present values to the hotel case with equipment taxes



Source: Author

In summary, the presented study case 4 shows that trigeneration systems to hotels can be profitable, but its profitability depends on economical indices which are not always ease to predict. Also, each case has different results, so a hotel with higher energy demand can shows itself more suitable to trigeneration systems than smaller ones. Moreover, if considered the use of national equipment to the system, the financial benefits would probably increase. In addition, this work gives parameters to investors decide if Brazilian hotels have or not potential to trigeneration systems, as each business has its own economical indexes they can use the sensitivity study to have an idea of profitability. Obviously a more detailed study has to be made, in order to have a more realistic scenario of financial benefits. Finally, in the point of view of primary energy conversion efficiency, the trigeneration system shows great results.

4. CONCLUSION

First of all, this thesis aimed to cover the lack of academic research on trigeneration systems in Brazil, mainly when it is related to small and micro trigeneration systems. Therefore, it was done a technical and economical evaluation of small and micro trigeneration systems to different buildings under distinct tariff policies. To do so, this work optimised the sizing and monthly scheduled the dispatch of trigeneration systems to each study case; evaluated the maximum net present value considering the variation of discount rate and US Dollar conversion rate; evaluated the grid dependence index, the discounted payback, the levelized cost of energy, and the primary energy ratio to the maximum NPVs.

In the hospital case the economic feasibility is on its viability threshold. So, the decision of investment has to be done according to the investor necessity and expectances. Also, the primary energy ratio presented on this case was good and the levelized cost of energy was reasonable.

The best financial benefit was obtained in the residential building case. It is possible to find a suitable discount rate with a reasonable net present value and discounted payback. Moreover, the primary energy ratio was good and the levelized cost of energy was also good.

The postgraduate building case is not economically viable. However, the primary energy ratio is good and the levelized cost of energy in reasonable. As in some situations the payback is lower than 15 years, it is possible to make the investment only to research purposes.

In the hotel case the economic feasibility is on also on its viability threshold. So, the decision of investment has to be done according to the investor necessity and expectances. In addition, the primary energy ratio presented on this case was considerably good and the levelized cost of energy was not good.

Therefore, the presented results show that there are financial and energetic advantages in the adoption of trigeneration systems in some situations. However, due to simplifications on the trigeneration system model, the presented results give an overview of possible benefits in the adoption of trigeneration systems. The financial feasibility of the system has to be analysed case by case, and preferably with more detailed data, taxes and model to give a more realistic picture of the benefits.

Also, this work shows the two limits of financial feasibility, thus, the maximum possible financial benefit is when taxes are not considered. While the minimum financial benefit is represented by taxes of 100%, which is a value above the actual taxes applied by Brazilian policies. So, once more, this thesis offers an overview of possible benefits on the use of trigeneration on Brazilian buildings.

In summary, trigeneration plants can be profitable and it is certainly an efficient way to adopt a reliable and controllable distributed generation. Therefore, it is possible to find situations in which the trigeneration plant can offer a high primary energy ratio, a fair levelized cost of energy, and in the meantime, it can provide financial savings with fair payback time.

A number of future works can be suggested from this thesis, such as:

- Consideration of part-load efficiency behaviour of equipment to generate a more realistic simulation of trigeneration systems, as all equipment will not operate on its rated characteristic all the time due to energy demand variation. The outcome will probably be worse than the results presented in this study to investors, but they will also represent the reality more accurately;

- Use of mixed integer linear programming to decide between the use of electric chiller or absorption chiller, and between electric boiler or gas boiler, giving more options to the investor. The optimisation process can be also more automatic, as it is possible to implement the prime mover, boiler and chiller size options inside the optimisation function, and not with external loops as was done is this thesis;

- The study of the impact of trigeneration systems on the distribution network can be another way to study such systems. As they can be fully controlled, they could be used to help on the safety and reliability of the distribution network;

- To expand and make the feasibility evaluation more realistic it is necessary to use prediction methods to load modification on the future, also to make evaluation of trigeneration systems to other tariffs policies, and consider the real taxes applied by the Brazilian government;

- The study of possible combination of solar thermal and photovoltaic technologies with batteries could be a good option to substitute the cogeneration unit (prime mover) and auxiliary boiler. This modification can make the trigeneration system more economically and environmentally sustainable;

- A more advanced study could be performed on the interaction of different distributed generation technologies (including non-renewable – e.g. cogeneration and trigeneration – and renewable sources of energy – e.g. photovoltaic and wind) and loads on the distribution network.

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