Energy Services for The Food Industry

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

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Abstract

The growing awareness of sustainability challenges contributes to the direction of EU policy and emerging of ecologically oriented start-ups. Although a number of entrepreneurial incentives have been facilitated, few of them have considered local gastronomy appliances as a potential area for energy efficiency improvement and means for electrical grid stabilization. This research investigates, in cooperation with a German start-up KOENA tec GmbH (https://koena-tec.com), the feasibility and market potential of combining two energy services for professional espresso machines: the increase in the energy efficiency and simultaneous provision of Frequency Containment Reserve (FCR) services.

The qualitative analysis of EU ecodesign and energy labelling policy together with interviewing industry representatives established a wider perspective for the presented topic. Three quantitative investigations were carried out to estimate the market potential for the selected energy services. Based on Statistical Classification of Economic Activities in the European Community (NACE) and sales information from gastronomy association, the stock size of espresso machines was estimated. The collected energy consumption data (60 days; ~1 second resolution) from a three group *La Marzocco* coffee machine allowed the calculation of the potential energy savings and disposable power for FCR services. The energy efficiency increase was approximated based on the examination of thermal flux between boilers and environment. Intermittent demand approach to coffee production was the foundation for generating load profiles of the appliance and, consequently, to forecasting disposable FCR power for daily time intervals.

Four scenarios for stock size quantity were prepared for 12 countries (total results in thousands of units:141, 180, 517, 616) covering 95% of EU population. The potential energy saving of a coffee machine during idle mode at night was approximated to be 4.51 kWh daily, whereas a coffee boiler's theoretical reduction turned out to be 0,73 kWh daily, all together allowing for savings of 25%. Furthermore, a following values of FCR disposable power for aggregation of 100 machines were estimated: night-time- 33,17kW, 8:00-10:00 – 39,33 kW, 10:00-18:00 - 42,65 kW, 18:00-20:00 – 36,9 kW, 20:00-21:00- 35,69 kW. Consequently, in the scenario including 3 and 4 group traditional machines and recommended switch off during nights a total savings of 39,3 mln euros were estimated.

The presented research verifies and confirms the feasibility of simultaneous reduction of energy use and provision of FCR services for espresso machines. Furthermore, the quantitative analysis of energy services may be considered an indicator for the future sustainability and entrepreneurial incentives.

Keywords

Energy efficiency, FCR, energy labels, intermittent demand

Resumo

A crescente consciência acerca dos desafios da sustentabilidade contribui para o alinhamento da direção da política da UE, bem como para o surgimento de startups ecologicamente orientadas. Pese embora vários incentivos empresariais tenham sido facultados, poucos consideraram os equipamentos gastronômicos como uma potencial área para a melhoria da eficiência energética e ao mesmo tempo para a estabilização da rede energética. Esta tese investiga, em cooperação com a startup alemã KOENA tec GmbH (https://koena-tec.com), a viabilidade e o potencial de mercado de combinar dois serviços de energia para máquinas de café expresso profissionais: o aumento da eficiência energética e em simultâneo a prestação de serviços de Reserva de Contenção de Frequência (FCR).

A análise qualitativa do ecodesign da UE e das políticas de rotulagem energética, juntamente com entrevistas com representantes da indústria, estabeleceu uma **perspetiva** mais ampla para o tópico apresentado. Foram realizadas três análises quantitativas para estimar o potencial de mercado para os serviços de energia selecionados. Com base na Classificação Estatística de Atividades Econômicas na Comunidade Europeia (NACE) e informações de vendas da associação de gastronomia, o tamanho do stock de máquinas de café expresso foi estimado. Os dados de consumo de energia recolhidos (60 dias; resolução de ~ 1 segundo) de uma máquina de café *La Marzocco* de três grupos permitiu o cálculo do potencial económico de poupança de energia e energia disponível para serviços de FCR. O aumento da eficiência energética foi aproximado com base na análise do fluxo térmico entre as caldeiras e o ambiente. A abordagem da demanda intermitente para a produção de café foi a base para a geração de perfis de carga do aparelho e, consequentemente, para a previsão de energia FCR descartável para intervalos de tempo diários.

Foram preparados quatro cenários para a quantidade de stock para 12 países (resultados totais em milhares de unidades: 141, 180, 517, 616) cobrindo 95% da população da UE. O potencial económico de poupança de energia de uma máquina de café em modo inativo (durante a noite) foi estimado em 4,51 kWh por dia, enquanto a redução teórica de uma caldeira de café acabou sendo 0,73 kWh por dia, todos juntos permitindo uma poupança energética de 25%. Além disso, foram estimados os seguintes valores de energia descartável para serviços FCR considerando a agregação de 100 máquinas: período noturno- 33,17 kW, 8: 00-10: 00 - 39,33 kW, 10: 00-18: 00 - 42,65 kW, 18: 00-20: 00 - 36,9 kW, 20: 00-21: 00- 35,69 kW. Consequentemente, no cenário que inclui 3 e 4 máquinas tradicionais do grupo e desligamento recomendado durante a noite, foi estimada uma poupança total de 39,3 milhões de euros.

Os resultados apresentados verificam e confirmam a viabilidade para a redução do consumo de energia e em simultâneo a prestação de serviços de FCR a partir de máquinas de café expresso. Além disso, a análise quantitativa dos serviços de energia pode ser considerada um indicador para a sustentabilidade futura e incentivos ao empreendedorismo.

Palavras-chave

Eficiência energética, FCR, etiquetas energéticas, demanda intermitente

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List of Acronyms

aFRR	Automatic Frequency Restoration Reserve
BKW AG	Bernische Kraftwerke
EFCEM	The European Federation of Catering Equipment Manufacturers
ENAK	Association for the Promotion of the Energy Quality of Commercial Appliances for the Catering Industry
EVA EMP	European Vending Association Energy Measurement Protocol
EWP	Ecodesign Working Plan
FCR	Frequency Containment Reserve
HKI	Association of House, Heating and Kitchen Technology
IDI	Inter-demand interval
mFRR	Manual Frequency Restoration Reserve
NACE	Statistical Classification of Economic Activities in the European Community
NBD	Negative Binomial Distribution
PG&E	Pacific Gas and Electric Company
RR	Restoration Reserve
SOM	Serviceable Obtainable Market
TAM	Total Available Markets
TOM	Total Obtainable Marker

List of Symbols

a	Thermal parameter [$Wm^{-1}K^{-1}$],
CF	Correction factor
C_p	Specific heat
CV^2	Squared coefficient of variation
k	Material conductivity [$W \cdot m^{-1} \cdot K^{-1}$],
q	Heat flux [W·m^{-2}],

List of Software

R Studio	Environment for R language
Microsoft Office	Standard programs for calculation, graphing and basic programming

Chapter 1

Introduction

This chapter gives a brief overview of the work. Firstly, it describes the background for this research and the role of KOENA tec start-up. Then it focuses on EU policy regarding energy efficiency, efficient design of products (eco-design) and energy labelling. Consequently, it presents a discussion about including coffee machines in ecodesign Working Plan 3 and briefly characterizes the major elements of balancing services. A brief literature review is presented in subsection 1.3. At the end of the chapter, the work objectives and document organisation are presented.

1.1 Context

The impact that climate changes and global warming have on human existence occupies the attention of a number of scientists around the world. It is estimated that human activities have been responsible for the increase of global temperature by around 1°C degree above pre-industrial level and are likely to cause further growth of global warming to 1.5 °C within the next three decades [1]. Due to that a number of incentives for sustainability transition, such as Paris Agreement, were proposed.

In order to mitigate the negative effects of global warming, EU prepared its own climate policy. Among other measures, EU emphasizes the importance of energy efficiency, setting an ambitious goal of 32.5 % improvement up to 2030 [2]. In order to fulfill this commitment, various actions are taken. One of them is the introduction of ecodesign policy, which supports low-energy solutions for broad spectrum of industries and products.

KOENA tec GmbH, a German start-up working on IOT & Energy solutions for gastronomy sector, has identified a possible area where the energy efficiency measures may be applied. KOENA tec believes that professional espresso machines have a high potential for energy savings and that they might contribute to the grid stability by providing energy services for transmission system operators.

The author of this thesis considers the KOENA tec's claim riveting and promising. Therefore, the scope of this research will be focused on the market opportunities for the combined provision of energy efficiency and services for the grid operation.

1.2 Background

1.2.1 EU Policy: Energy Efficiency and Energy Labelling

A number of authors have already recognized energy efficiency as a key factor to industrial competitiveness, energy security as well as direct benefits in the field of environment [3]. Its importance is also reflected by European Union policy. For instance, the 2020 climate & energy package targets 20% of energy efficiency improvement whereas the directive DIRECTIVE (EU) 2018/2002 [2] aims at 32,5% improvement up to 2030. In order to achieve this goal, various methods are applied. The EU commission divides its actions into five main categories: energy efficient buildings, cogeneration of heat and power, financing energy efficiency, heating and cooling, energy label and ecodesign [4]. The last category lies within the scope of this thesis and will be discussed further.

The EU ecodesign policy, based on DIRECTIVE 2009/125/EC[5], creates a framework for compulsory environmental requirements for 31 selected groups of products within EU. It includes energy-using devices as well as other energy-related products. The main goal of the ecodesign directive is not only to decrease the energy consumption, but also to mitigate the negative impacts on the environment. For example, the policy promotes inclusion of recyclable elements, which simultaneously enhance the reparability of appliances. Additionally, it contributes to the EUs' energy security due to energy resourses' import reduction and generates up to a total of million job openings.

The regulation also supports labelling of products' energy use, which results in reliable indications for customers, whether the purchased products maintain high levels of energy efficiency and have low impact on the environment. Furthermore, they do have also a strong monetary meaning: it is estimated that standards and labels will bring up to 490 euro of savings on energy costs for averaged households[6].

The methodology of the implementation of ecodesign policy is described in the Ecodesign Working Plans (EWP), currently in version 2016-2019[7]. It is built on 5 mutually reinforcing dimensions[8].

1. Energy security, solidarity and trust.
2. A fully integrated European energy market.
3. Energy efficiency contributing to moderation of demand.
4. Decarbonizing the economy.
5. Research, Innovation and Competitiveness.

The 3rd dimension, namely, energy efficiency contributing to moderation of demand, is of special importance for the scope of this thesis as well as for KOENA tec project. Although, within the given area the EU emphasises two main sectors: building and decarbonized transport, the ecodesign working program includes a variety of products groups.

It is crucial to point out, that one of the goal of EWP is to prepare "an indicative list of energy-related product groups which will be considered priorities *for the undertaking of preparatory studies and eventual adoption of implementing measures*" [5]. It is thought relevant to investigate the EUs' reflection on appliances, which are within the scope of this thesis, i.e., the professional coffee machines.

1.2.2 The Ecodesign Working Plan 3: Tertiary Coffee Machines

At the initial stage, the European Commission considered including tertiary (non-domestic) hot beverage equipment in the EWP 3[9]. The decision was, however, changed, resulting in dropping tertiary hot beverage equipment from EWP3. It is thus relevant to discuss this decision and to describe the market segment more deeply.

The EWP 3 divides tertiary hot beverages in three main categories:

1. Free standing Hot Beverage Machines
2. Table-top Hot Beverage machines
3. Professional Espresso Machine

Free Standing Hot Beverage Machines are considered to play a significant role in highly populated areas. They are capable of preparing plenty of drinks (coffee, hot chocolate, etc.). Table-top machines are, on the other hand, designed mainly for offices, but also for hotels and restaurants. They are usually highly automated, so that basic drinks can be prepared directly by company workers or hotel guests.

However, only professional Espresso machines are relevant for the scope of this thesis and they will be described in more details.

Espresso machines brew coffee by forcing hot pressurized water through finely grounded beans. Depending on the automation level of the brewing process, an espresso machine can be either traditional or automatic. In both cases the water is pumped from a water reservoir or constant water supply. Then it is heated up and flows to group head, which is connected to porta filter. Next, when a pump is switched on, the brewing process starts.

However, the important question is: what is the potential for an increase of energy efficiency? In order to answer it, three relevant factors have to be addressed:

1. Stock of coffee machines
2. Energy consumption
3. Feasibility to increase energy efficiency

Due to the scarcity of data, it is challenging to estimate the stock of coffee machines [10]. The approach introduced in EWP 3 assumes that each coffee machine corresponds to one restaurant. Next, a number of restaurants are collected from Eurostat. It projects to 1.45 million installed units of non-tertiary coffee machines in Europe (2010). Taking into consideration a growth rate of 1.5%, the EU forecasted that the quantity of professional coffee machines is going to reach 1.680 million in 2030[1]

For the estimation of energy consumption, EWP 3 followed a field test performed by PG&E (2000). The test indicated an energy use of 15.8 kWh per coffee machine per day. However, EWP 3 decreased this value to 12 kWh per day due to assumed technological progress. Finally, it was concluded that such an appliance consumes 3,750 kWh per year assuming 6 days of use in a week, which is equal to c.a. 6.3 TWh of aggregated power consumption in 2030 in EU.

As for the potential of improvement, the EU study was based on the same PG&E test. It stated, as it is described in EWP 3, that there is a possibility to reduce energy use by 42% with better insulation of boilers. However, It was pointed out that this progress might have already been made. Furthermore, the final report from task 3 of EWP 3 mentions that according to The European Federation of Catering Equipment Manufacturers (EFCEM) *"(..) little improvements could be technically done on professional espresso machines."* The argument behind this statement is that professional coffee machines have to be ready to serve coffee anytime during the day, hence the auto-power down functions are not suitable for cafes and bars. Moreover, it is already a common practice to switch off the appliances during night, whereas additional isolation upgrades might negatively impact some of the machine's functionality, for instance limit cup warming possibility. To conclude, it is estimated that only 0,6 TWh of energy can be

[1] The presented value of 1.680 million in 2030 is taken directly from EWP 3, although calculation based on the methodology results in 1.920 million units. The author of this thesis assumes that methodology presented in EWP 3 is not fully described and decides to follow the EWP 3 outcomes.

saved in the segment of tertiary coffee machines.

Dropping tertiary coffee machines from EWP 3 is however challenged by Eric Bush in his Preliminary Study on Hot beverage Equipment [11]. In contrast to EWP 3, Eric Bush claims that 10% upper bond of improvement for professional espresso machines is strongly underestimated. Based on “Brief plausibility check of the saving potential estimates for hot beverage vending machines” by A. Nipkow and as well as the ENAK database, Bush suggests that savings potential of professional coffee machines should be around 40% and consequently emphasises the appliances’ significance for EU green policy goals.

The section above points out some of the problems encountered in the current state of research. First of all, the scarcity of data reflects the need to establish a more accurate methodology to forecast the stock values of espresso machines. Secondly, the estimated energy consumptions are underrated according to KOENA tec’s previous internal studies. Last, but not least, the suggested potential of energy may strongly depend on the size of a coffee machine and should be further investigated. Consequently, as mentioned by Eric Bush, an in-depth analysis is vital to determine the importance of professional coffee machines for a transition to a sustainable energy system.

1.2.3 Ecolabelling and Standards – The Case of Coffee Machines

Complementary to the introduction of ecodesign, European Commission recommends implementing the eco-labels policy. Due to the scope of the thesis, only the most relevant for tertiary coffee machines will be presented and discussed.

Although various well-recognised and certified by third party eco-labels already exist, they are not that common in the segment of professional coffee machines. Nonetheless, there are two main reasons why it is crucial to consider them more deeply. First of all, according to Bush, the implementation of this solution is the most effective way to increase energy efficiency of coffee machines [11]. Thus, it is relevant to discuss their upcoming role and the corresponding policy of main actors: countries, organizations and manufactures. Furthermore, the already existing labels can indicate the direction of improving energy efficiency.

The most relevant energy labels related to the topic of this thesis are listed in Table 1.1. Apart from the respective logo and a brief comment, the 3rd and 4th columns indicate the standard type and the segment categorization respectively. One may point out that espresso machines are considered to be important for well-established labels (Energy Star, Blue Angel) as well as for new players from engaged organisations (HKI, Topten). Although the process of including espresso machines to energy labels seems to be a long-term project, this trend indirectly strengthens the KOENA’s business idea. Not only it confirms the importance of the gastronomic sector for the energy efficiency market, but it also may play a role of marketing factor.In order to study the potential areas for energy savings in a coffee machine, it can be very relevant to investigate the procedure of granting energy labels, which is mostly based on preidentified standards. Their function is to guarantee that uniform norms will be applied to each of the appliances. Currently, there are five main standards:

Table 1.1 List of selected eco-labels. In the third column a name of used standard for given eco-label is mentioned. Column 'segment' corresponds to categorization for domestic and non-domestic appliances.

Logo	Description	Standard	Segment
	Energy star One of the oldest and most recognizable ecolabels. Includes coffee brewers, not yet professional espresso machines.	Own	Commercial
	Blue Angel The oldest German ecolabel. Currently, includes only bulk type of coffee machines. Well known mark among European countries.	Own	Domestic
	Nordic Swan Ecolabel A voluntary license for vast group of products in Nordic countries. Frequently applied not for a specific product, but the whole segment of particular company	EVA EMP 3.1 b / DIN 18872-2	Commercial
	Prokilowatt Applied by both ProKilowatt and Topten. Products with such label are eligible for 150 CH subsidy within Switzerland.	DIN 18872-2	Commercial
	Energy Efficient by HKI The label is awarded by HKI organization, which possess a large database of espresso machines with relevant energy-related values.	DIN 18872-2	Commercial

1) **EVA EMP 3.1 B - VERSION 3.1B – October 2016** [12]**:** Test protocol for the measurement of energy consumption in vending & dispensing machines; part 2 hot and hot & cold drinks machines.
2) **DIN 18873-2:2016-02:** Methods for measuring the energy consumption of commercial kitchen appliances - Part 2: Commercial coffee machines.
3) Measuring Method and Calculation Topten & SAFE Formula for the Electricity Consumption of Coffee Machines for Household Use.
4) **ENAK / SVGG** [13]**:** Test definition for coffee machine data sheet.
5) **EN 60661:** The methods for measuring the performance of electric household coffee makers.

Out of these five, the first two **EVA EMP 3.1 B - VERSION 3.1B – October 2016** and **DIN 18873-2:2016-02** are most frequently used and are considered to be the foundation for possible standards' unification [11]. For the purpose of this thesis, the EVA Energy Measurement Protocol Version 3.1 October 2016; Part 2 Hot and Hot and cold drinks machines will be briefly described. Regarding coffee machines, there are five relevant measurements [12]:

1. **Heat up phase measurement (HU):** the measurement of energy needed to heat up the appliance. Once the machine has been installed and set up for normal operations, the tested machine and energy meter are to be switched on. The test is completed when the machine thermostat switches off the heating device. At this point, the measured energy consumption is recorded.
2. **Idle state measurement (IM):** measurement of energy during idle state. All the features have to be switched off for 24 hours. After that time, the measurement device is switched on for 24 hours. The average value for one hour is the result.
3. **Vending phase measurement:** the test defines the necessary energy for drink preparation and delivery. Drinks should be taken at a rate of one drink every two minutes. Total drinks volume should be at least equal to the boiler size and its quantity should not fall below 30. The resulting energy should be decreased by Idle state energy.
4. **Energy saving mode (ESM):** the test measures the energy use after boiler cools down to set temperature. Additionally, cool down duration and cool down energy are also noted.
5. **Heat up from energy saving mode:** the test measures the energy needed to return to normal working mode from energy saving mode. After ESM is finalized, the energy is measured until the machine's thermostat switches off.

Although measurements' procedures presented above seem to be established mostly for typical vending machines, they are also followed for the espresso - kind coffee machine. Furthermore, this categorization of tests will impact the methodology in the quantitative part of this thesis. The division between *Idle state* measurement (night cycle of the tested machine) and *Vending phase* measurement (day cycle of the testes coffee machine) will be fundamental for energy efficiency and FCR potential analysis. The heat up phase measurement will be, on the other hand, considered a relevant factor in the estimation of night savings for coffee machines.

1.2.4 Balancing services

As mentioned above, KOENA tec considers the extension of a coffee machine functionality by an addition of extra services for the grid operation. Thus, it is relevant to briefly discuss various possible options and examine which service is most appropriate when taking into consideration the technical characteristics of a coffee machine.

Due to the physical characteristics of electricity transmission, i.e., a constant need for balance between consumption and production, it is relevant for the security of the grid to provide a range of ancillary services. It includes the balancing services, which, based on EU guideline on electricity balancing [14], consists of capacity and energy services and aim at a continuous maintenance of the frequency of the system with respect to a predefined *stability* range. It is relevant for this thesis to briefly describe the different balancing services, so that the most suitable one can be selected as an additional value to the increase of energy efficiency of coffee machines.

The typical behaviour of a coffee machine consists of relatively significant power changes at the moments when extra heat is necessary to preserve the temperature of the boiler or produce hot water and steam flow. Due to that, we will focus on the balancing of energy, which demands very fast switch on triggering and short duration times, rather than on capacity services. There are currently four different types of reserves:

1. Frequency Containment Reserve (FCR)
2. Automatic Frequency Restoration Reserves (aFRR)
3. Manual Frequency Restoration Reserves (mFRR)
4. Restoration Reserve (RR)

The above categorization is mainly based on their actual difference in the duration of delivery as well as the response time. Whenever the grid frequency happens to have a drop or a spike, FCR is automatically activated (within maximum 30 seconds period). The stabilization of the grid with the use of FCR involves a cooperation of every TSO within the synchronous area. Next, after a duration of a few minutes, frequency restoration process takes place. It includes automatic activation of Frequency Restoration Reserve (aFRR), whereas launch of manual frequency restoration reserves depends on a direct request from TSO. The purpose of FRR is to restore the nominal value of the grid frequency. The last step, which supports or replaces FRR, is the activation of restoration reserve (RR). RR is usually switched on after 15 minutes and participation in the service is not considered mandatory in EU (however such service should be provided by the system). The graphical representation of the reserve functionality is depicted in Figure 1-1. According to the represented diagram, the general framework of the load-frequency control consists of three main phases. Initially, after the disturbance of the frequency occurs, joint action of FCR is activated for the whole synchronous area. The process starts almost immediately, when a disproportion between production and demand of electricity takes place. Consequently, the grid frequency is stabilized. If the FCR is not sufficient, it is then replaced by FRR, so that frequency is being restored to a given setpoint value. After that, RR supports or replaces the FRR for further grid stabilization.

One can point out that coffee machines can be most suitable to provide FCR services. It is due to the short duration time of FCR, so that extensive or incomprehensive consumption of electricity will not drastically change the thermodynamic parameters of boilers. Consequently, coffee production quality will be scarcely influenced, or, at least, the impact will be lower than in the case of FRR or RR.

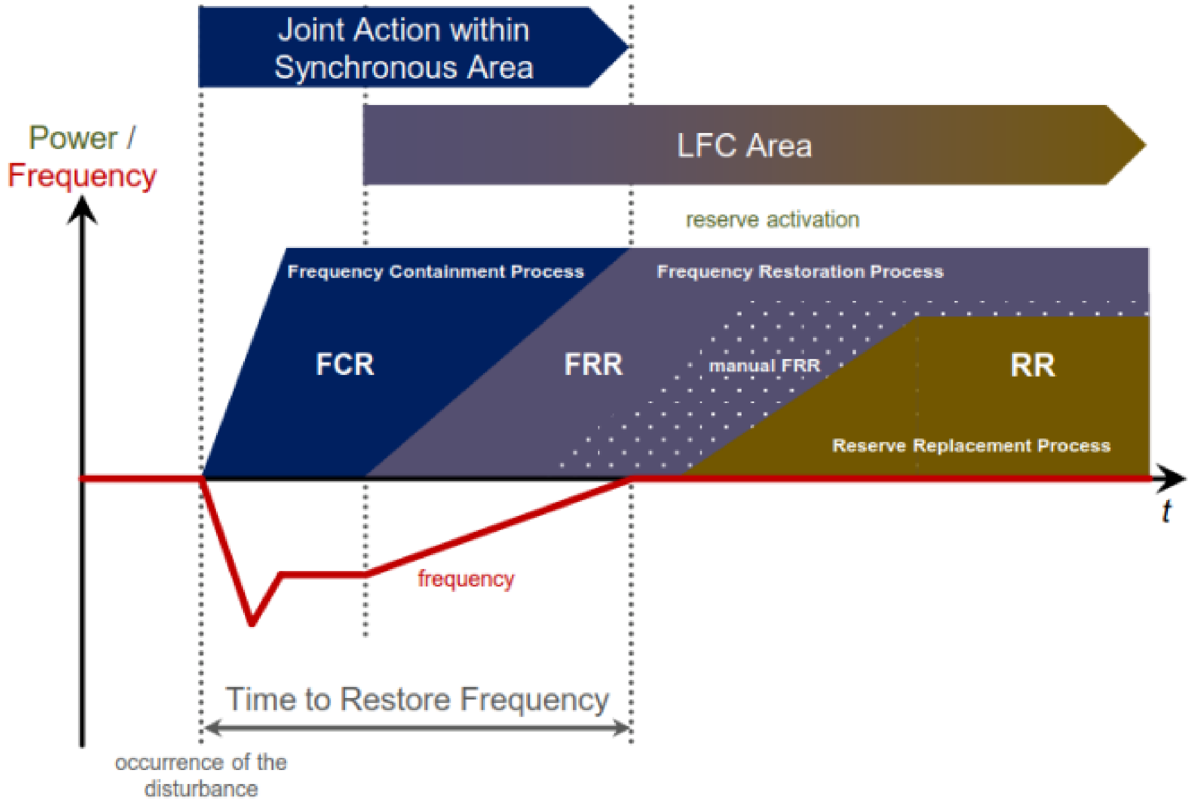

Figure 1-1 Reserve activation structure as an answer for frequency drop (red line) -ENTSOE [15].

The general process of providing balancing services is uniform in the entire EU and is regulated by common guidelines (System Operation Guideline). The harmonized rules ensure the security of the grid and allow to extended cooperation between EU members. Article 153 of COMMISSION REGULATION (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation describes FCR dimensioning whereas Article 154 discusses technical minimum requirements. The detailed analysis of guidance is not in the scope of the thesis. However, it is important to point to out that due to its existence, the conclusion drawn in this chapter is valid within all members of EU.

1.3 Related Works

The literature review shows that there is a number of attempts to emphasize gastronomy importance for the need of sustainability. G. Jacobs and P. Klosse in “Sustainable Restaurants: A Research Agenda” (2016)[16] indicate the three major areas of sustainability promotion for gastronomy points: the incentives of restaurants for coming up with ecologically-friendly menu, the role of a demand for “green” menu as well as an investigation of restaurant’s offering (product sustainability).

Some authors also suggest direct examination of the impact of gastronomy energy consumption. For instance Willy Legrand et al. claim in “A Review of Restaurant Sustainable Indicator”[17] that even “*(…) if the restaurant does not have the right conditions or financial means to install renewable energy systems (…) it should consider buying green energy”.* Furthermore, the authors advocate for offsetting carbon emissions as an alternative to mitigate the environmental effects, which is understood as a contribution to initiatives decreasing carbon footprint. One may point out, that this idea is adopted by KOENA tec. GmbH. The KOENA tec.’s project of increasing energy efficiency and providing FCR from an aggregation of espresso machines can be considered a direct implementation of W. Legrand’s concept.

Over time, a few studies in the broader literature have examined, how these various approaches to the gastronomy sustainability can be evaluated. Samantha Mudie and Maria Vadhati in their research “Low energy catering strategy insights from a novel carbon-energy calculator”[18] provide quantitative insights about carbon and energy impacts of a restaurant. Although, various scenario-based recommendations leading to energy efficiency improvement are presented, there is lack of detailed analysis of espresso machine saving potential.

It is significant to point out, that there are existing analysis regarding coffee machines ([11], [19], [20]) energy use, but their research scope remains limited. The studies examine the value of potential energy savings of espresso machines (10-40%[11], [20]), the size of stock (above 1.5 mln units in Europe[20]) and evaluate possible areas of improvement for gastronomy kitchens[18].

Furthermore, previous gastronomy studies seem to be focused almost exclusively on the direct reduction of carbon footprint. However, the transition to zero-emission economy requires a number of other accompanying services, such as for example balancing services for the grid.

1.4 Objectives of the Thesis

Against this background, it is relevant to fulfil the highlighted gaps and investigate the possible combination of energy services (energy efficiency & FCR provision) from the perspective of coffee machine appliances.

The overall goal of this work is to examine KOENA tec’s idea and to estimate the potential market of combined energy efficiency and FCR services provided by coffee machines. The verification of this joint market proposal is the primary problem of this thesis. Furthermore, if such a concept is viable, it will be important to provide approximate values of energy savings and disposable power for FCR services. On the other hand, in order to estimate the size of the market, it will be necessary to focus on forecasting the stock size of coffee machines.

The thesis will then include three main quantitative parts:

1. Estimation of the stock quantity
2. Estimation of energy savings per coffee machine
3. Forecast of disposable power for FCR services

Each of the parts will consist of a methodology and a discussion over results. Furthermore, in the final chapter of the thesis, a holistic approach will be presented, so that a complete analysis, based on all three quantitative parts, can be carried out.

1.5 Document Organization

The following part of the thesis will consist of five sections. First three chapters will investigate three major areas of interest. They all consist of four analogical subchapters: introduction and objectives, proposed methodology, available data and results and discussion. Chapter 2 focuses on the coffee machine stock estimation and it is based on the analysis of data from national statistical offices and coffee machine sales information. Chapter 3 examines a potential energy efficiency improvement of an espresso machine accordingly to a field test at one of Stuttgart cafes. The next chapter concentrates on the second relevant energy service: provision of FCR. It addresses the question of possible use of a coffee machine as a source for balancing services.

The research demonstrated in sections 2-4 is then consolidated and discussed in chapter 5. It includes a presentation of combined quantitative results and provides insights for simultaneous combination of both previously analysed energy services. At the end of this work, conclusions are drawn in chapter 6. Additionally, limitations and future work opportunities are indicated in subchapter 6.2. Results not presented in the main part of thesis are depicted in the Annex.

Chapter 2

Coffee Machine Stock Estimation

This chapter provides a detailed description of the selected approach to coffee machine stock estimation. It consists of 4 main parts. The subchapter 2.1 and 2.2 briefly summarize the obstacles corresponding to estimation of the coffee machine stock size and present the methodology used for data collection and analysis from two major sources. The subchapter 2.3 focuses on presenting available data, whereas the results are included in the last section of the chapter.

2.1 Introduction and Objectives

One of the most important challenges of a young start-up such as KOENA tec is to estimate the market potential for its services. KOENA tec plans to follow a general, well known TAM SAM SOM [21] approach, which divides the market analysis in three main domains: TAM - Total available market, SAM - Serviceable Available Market and SOM - Serviceable Obtainable Market. The TAM part describes the global total revenue opportunity. SAM is an inclusion of TAM, which takes into consideration various typical business constraints, for instance competition or distribution. SOM, on the other hand, quantifies the value of actually realistic part of SAM. The scope of this thesis is limited to the evaluation of total available market of services for coffee machines - TAM.

The investigation of market size described in this chapter will have a top down approach and will start with an identification of a relevant kind of espresso machine for KOENA tec. Afterwards an attempt to estimate a number of operating entities with a high probability of owning such a coffee machine will be presented (TAM). Furthermore, these values are going to be adjusted with sales information from the HKI[22], [23], an industrial association of House, Heating and Kitchen Technology.

As it was mentioned earlier, the aim of KOENA tec is to develop more sophisticated methods to increase energy efficiency in kitchen appliances, especially for coffee machines. It is though necessary to define what kind of an espresso machine will be of interest for KOENA tec.

There are three main categorisations of coffee machines: by **purpose of use,** by a **level of automatization** and by **technology used for heating**. The first one divides devices by the **purpose of use** for private and commercial. Usually, the latter have higher durability, capability and power demand. Another way to categorise coffee machines is according to a **level of automatization**: there are automatic and traditional machines. Traditional ones enable baristas to brew more individual and customized coffees and as such possess higher esteem. Due to that, as well as based on interviews with representatives of gastronomy industries, one may point out, that professional cafes and restaurants possess mostly traditional, commercial coffee machines.

From a consumer point of view, a typical machine has to deliver different kinds of drinks, such as espresso or latte. Brewing a coffee demands a high temperature, around 92-94 degrees. However, for some drinks, like latte, it is necessary to use hot and richly textured milk. This is achieved by steam production, which thermal parameters differ strongly from brewing water. Consequently, the third categorization divides the machines by **technology used for heating**, particularly for the following types: single boiler, double boiler, heat exchanger or thermoblock. Bearing the aim of this thesis in mind, there is no need to describe them in details. However, it is important to point out the difference between a thermoblock and the rest of technical solutions. A thermoblock is a thick metal element, which rapidly heats up pumped water bursts for brewing or steam production. Therefore, thermoblock appliances do not function as heat storage and cannot be considered relevant for KOENA tec. Conveniently, due to low popularity of solution, these insights do not impact our investigation.

Another important factor to examine is the size of a boiler and the machines' power consumption. Both of them are strongly correlated not only with each other but also with a number of spouts (groups). The number of groups is a common industry classification of coffee machines. Each additional spout allows to simultaneously produce higher quantity of drinks, for instance an extra double spout enables brewing two additional single espressos at the same time. Moreover, a higher number of groups increases a daily possible quantity of products with the same stable quality and it is often associated to bigger and more complex heating technology: for example *La Cimbali M100* is equipped with separate boilers for each spout. Certainly, KOENA tec would take advantage of coffee machines with higher power consumption and boiler size. Thus, the company should focus on the biggest, three and four group machines, whereas the inclusion of a two group machine is a potential trade-off between increasing market size and decreasing KOENA tec's service value per coffee machine unit. Having considered all of the above factors, we limit the analysis presented here to commercial, professional three and four group coffee machines.

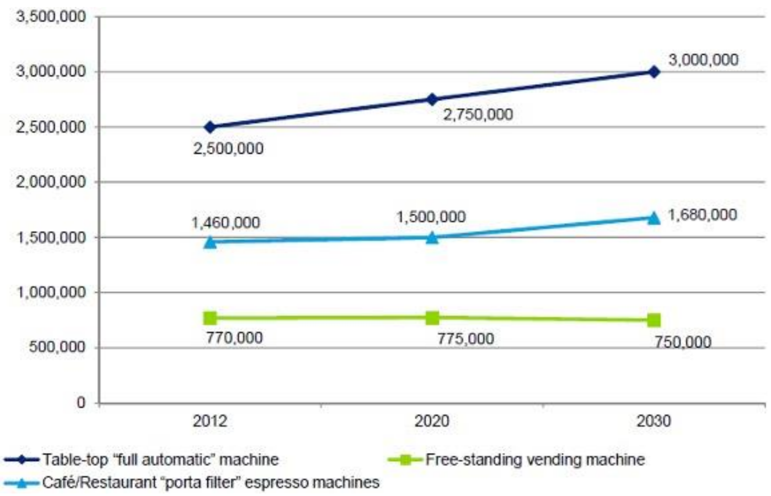

Figure 2-1 Estimation of stock quantity for various coffee machines [20]

Although the problem of scarcity of data for tertiary coffee machines was already briefly discussed in subchapter 1.2.2 [11], [20], it has to be addressed more deeply. A study prepared in Eco-Design Working Plan 3 2016-2019 and other research conducted by E. Bush claim that there is no database with accurate quantities of professional coffee machines worldwide, as well as in Europe. Eric Bush in his Preliminary Study on Tertiary Hot Beverage Equipment [11], in which he estimates the number of units, follows the same methodology as Eco Design Working Plan 2016-2019. This methodology assumes that each of the existing restaurant owns one machine. The number of restaurants is based on Eurostat statistics from 2010 and projected until 2018 with an average lifetime of 15 years and an annual sales growth rate of 1.5 %. This growth rate value was assumed without any reliable basis and could not be confirmed by European Federation of Catering Equipment Manufacturers [20].

2.2 Proposed Methodology

The above description highlights the task's difficulty and questions the methodology. Consequently, a new approach would be of interest. The herein proposed methodology will proceed in two stages. The first part will focus on collected data from statistical offices. Based on this data, a number of gastronomy points will be estimated. Next, a correlation between gastronomy point and a coffee machine will be defined. In the second part, out of the estimated number of coffee machines, a selection of coffee machines characterized by high potential for providing energy services.

In the first place, it is crucial to establish a better procedure for restaurant selection. To do so, more detailed data from a reliable source is needed. It was decided to focus on data provided by national statistical offices based on the Statistical Classification of Economic Activities in the European Community (NACE) [24] system.

NACE is a standardized industrial classification commonly used in Europe. The current version, called revision 2, follows a UN ISIC classification revision 4 and provides a structured framework for collecting information about economic activities. It consists of four hierarchical levels:

1. the first level (sections) identified by alphabetical letters,
2. the second level (divisions), identified by a two-digit numerical code,
3. the third level (groups) identified by a three-digit numerical code,
4. the fourth level (classes) identified by a four-digit numerical code.

Although, even if it turned out that data provided by various countries are classified with different level of details and sometimes with slight variations in a third and fourth level of NACE code, the reliability of information seems to be very high.

Five categories of NACE were preselected in accordance with their high probability of using professional commercial three and four group coffee machines:

1. 56. Food and beverage service activities,
2. 561. Restaurants (including mobile food service activities)
3. 56101 Traditional restaurants
4. 56104 Cafes
5. 563 Beverages establishments

For all the above NACE categories two parameters were collected from national statistical offices: the number of active enterprises and the revenue. The research scope was limited to the following countries: Germany, Switzerland, Italy, Belgium, Spain, Portugal, Greece, Poland and Austria for periods from 2013 to 2018 with a yearly resolution. Data for division 56 was available for all the chosen countries. However, in some cases, statistical information about its subsets was missing – still the majority of 3-digit data was available for the countries. In order to approximate the missing NACE subsets of data (for instance three digit 561 from 56), it was assumed that given ratio of missing subset to the upper set was equal the respective mean ratio of available data. Consequently, by obtaining mean ratio of subset to its direct upper level category for accessible data (for example the mean value of all existing 561 to 56 ratios), one could estimate the missing values with the given formula:

$$subset_i(X) = X \cdot mean\left(\frac{subset_{i,j}(X_j)}{X_j}\right) \quad (1)$$

Where j denotes data with available X and $subset_i(X)$.

It was then necessary to define which combination of preselected NACE categories can effectively reflect all the economic activities with targeted espresso machines. Due to data scarcity and various national level of granularity, four main definitions were established:

a. 5-digit NACE code subset: **56101: Traditional restaurants** + **56104: Cafes**
b. 2-digit NACE code whole group **56: Food and beverage service activities**
c. 3-digit NACE code subset: **561: Restaurants +563: Beverages establishments**
d. 3-digit/5-digit hybrid: **56101: Traditional restaurants + 56104: Cafes +563: Beverages establishments**

After careful consideration it was concluded that definition (d) is too detailed and data for a majority of countries would have to be approximated. On the other hand, definition (a) was questionable due to narrowing down too much the input information by not taking into account the group 563. Consequently, definitions (b) and (c) were selected to form the base for market estimation. Note that although this data describes a number of independent legal companies (LC), it is assumed that they represent separate gastronomy locals (GL) due to lack of other indicators. Detailed quantitative insights will be presented in the chapter Results.

Additionally, a so-called correction factor based on data on sales volumes in the sector ([22], [23]) was established to improve the quality of the obtained results. The correction factor is presented to measure how many of the estimated coffee machines are actually relevant. In other words, what is the percentage of coffee machines with a sufficiently high energy use to qualify for increase of energy efficiency and providing FCR services. Namely, it is vital to evaluate the percentage of professional 3 and 4 group appliances in selected countries. In order to do so, a ratio of sales volume of professional coffee machines to all coffee machines' sales volume will be obtained from sales data. This ratio will be later multiplied by a quantity of coffee machines according to NACE system. Consequently, a value of professional coffee machines in given country will be estimated.

The sales data was available for year 2019 and 2018. The information included in the report consisted of two main data sheets: the sales of automatic professional coffee machines, and the sales of traditional professional coffee machines. The section of the traditional machines include segmentation by the number of machine's groups. For the purpose of this research, it was assumed that sales distribution of espresso coffee units corresponds to the distribution of espresso machines in the restaurants. Consequently, a correction factor was defined:

$$CF_{i,j}^{3,4} = \frac{S_{i,j}^{3,4}}{S_{i,j}^{total}} \tag{2}$$

Where:

$S_{i,j}^{3,4}$- sales of 3rd and 4th group of traditional coffee machines per i country and j year

$S_{i,j}^{total}$ – total sales of coffee machines per i country and j year

or

$$CF_{i,j}^{2,3,4} = \frac{S_{i,j}^{2,3,4}}{S_{i,j}^{total}} \tag{3}$$

Where:

$S_{i,j}^{2,3,4}$- sales of 2nd, 3rd and 4th group of traditional coffee machines per i country and j year

$S_{i,j}^{total}$ – total sales of coffee machines per i country and j year

As it can be noticed, both $CF_{i,j}^{3,4}$ and $CF_{i,j}^{2,3,4}$ describe the ratio of targeted coffee machine sales to the total coffee machine sales per country and per year. These factors will be used to adjust the stock of espresso machines in the restaurants to only selected subset of 3rd and 4th or 2nd,3rd and 4th group units. Similarly, to the studies conducted by E. Bush and the EU, it is assumed that each of the entity owns one coffee machine: Restaurant factor (R)= 1. Thus,

$$Espresso\_units_{i,j}^{3,4} = CF_{i,j}^{3,4} \cdot GL_{i,j} \cdot R \tag{4}$$

$$Espresso\_units_{i,j}^{2,3,4} = CF_{i,j}^{2,3,4} \cdot GL_{i,j} \cdot R \tag{5}$$

Where:

$Espresso\_units_{i,j}$ – number of professional traditional espresso machine with selected number of groups in superscript, $CF_{i,j}$ – correction factor for selected number of groups in superscript, GL – number of gastronomy locals, R – restaurant factor, subscript i – I country, subscript j – j year.

2.3 Available data

Previous studies have shown the problem of data scarcity for professional coffee machine market [11], [19], [20]. In spite of intensive data investigation throughout various statistical sources such as EUROSTAT or national statistical offices, no direct, accurate and holistic information was found. A similar conclusion was reached after searching a great deal of thematic websites (https://clivecoffee.com, https://hki-online.de/ and others). Therefore, another approach was adopted. During the Intergastra(https://www.messe-stuttgart.de/intergastra/), a recognizable hotel and gastronomy fair held between 15-19 February 2020 in Stuttgart, the author of the thesis had an opportunity to discuss the issue with representatives of major espresso manufactures and gastronomy businesses (Thermoplan, WMF, Rex Royal, etc.). Unfortunately, the collected data was very scattered and often mutually exceptive. Furthermore, a few companies mentioned an existence of detailed inner reports about stock information, which unfortunately are confidential. Due to that, the author of the thesis together with KOENA tec, started preparing a structured, more detailed interview framework.

This methodology was planned to have been used during the Internorga fair 13-17 March 2020. Unfortunately, because of the COVID 19 crisis, the trade fair was cancelled. Thus, only the quantitative and qualitative results from Intergastra interviews were structured and saved as an Excel file. For the sake of completeness, it is worth to mention the availability of different paid reports on coffee markets, for instance, Grand View Research offers "Coffee Machine Market Analysis And Segment Forecasts To 2025". A free sample of this report was requested and investigated [5]. However, the market study seems not to align with this thesis purpose and focus mostly on the revenue rather than on the number of espresso units. Therefore, as a result of this, and also taking into account the uncertainty about the report quality and its high price, the purchase idea was rejected. Thus, it was decided to follow the methodology described in 2.2.

As it was mentioned before, the data provided by national statistical offices have various level of granularity and correspond often to different periods of a year. Moreover, small discrepancies occur between a fourth levels of NACE system. In spite of that, the accuracy of information is believed to be very high because international law requires countries to keep them open to the public.

Although it would be interesting to compare statistics from a greater deal of countries worldwide, only the most relevant regions were investigated, taking into account KOENA tec's business strategy and time limit. A few factors were taken into consideration: the countries' geographical position, their access to the market and its potential size, local customs related to drinking coffee and, in case of Poland, also the author's personal sympathy. Germany was a natural candidate, because of KOENA tec localization in Stuttgart, its biggest economy in Europe and already developed network of partners (i.a. Gruppo Cimbali Deutschland GmbH). Similarly, the already signed agreement of cooperation between KOENA tec and international multi-utility Swiss BKW AG about add-on services (FCR & predictive maintenance) makes Switzerland indispensable. These companies are followed by a number of EU Mediterranean countries such as France, Spain, Greece, Italy as well as Belgium and Portugal with traditional affection to coffee. Especially Italy is of great importance, since a huge majority of manufactures of traditional espresso machines is located in Apennine Peninsula.

Collected data for year 2016 is presented in Table 2.1. Five elements of NACE code are shown for 12 countries. Fields coloured with red were approximated. The scarcity of information is especially visible for Poland and Switzerland, for which only I56 is given. Spain and Italy turn out to be leaders in terms of all gastronomy locals. One may point out a high number of professional restaurants in Italy and

France, which seems to reflect general intuition.

Table 2.1 Statistical data for selected countries according to NACE categorization. Coloured numbers were approximated.

Countries / NACE code	**Number of legal entities of selected economical areas in 2016**				
	56	**56.101**	**56.104**	**561**	**563**
Poland	95895	*34202*	*1957*	*56396*	*34997*
Germany	184449	79958	11878	133555	35104
Switzerland	23481	*8375*	*479*	*13809*	*8569*
Belgium	45165	*16999*	*973*	28029	13214
Italy	273864	99909	844	146089	123866
France	218796	99038	353	168338	38800
Spain	281014	*45843*	*2623*	75591	191458
Portugal	75701	16047	1255	29893	44621
Austria	30948	*16832*	*963*	27754	2388
Greece	88127	*26543*	*1519*	43766	40465
UK	142019	*56574*	*3237*	93285	48734
Sweden	24953	*15133*	*866*	24953	9106

2.4 Results and Discussion

According to the methodology described in section 2.2, this part of the thesis will focus on the estimation of coffee machines stock in the most relevant countries from KOENA tec's point of view. It will be investigated basing on two main sources: HKI and National statistical offices. First of all, both datasheets will be discussed separately to provide baseline market insights. Secondly, the conclusions formed accordingly to the data from National Statistical Offices will be adjusted with the correction factor from sales distribution.

The national statistical offices categorize the collected information accordingly to NACE system. For the clarity of this chapter and the readers' convenience, we will consider relevant gastronomy locals (GL) as those qualified by 3-digit NACE code subset: a combination of 561: Restaurants +563: Beverages establishments. The pie chart in the Figure 2-2 shows these estimated numbers of GLs for selected countries. As it can be seen, more than 50% of GLs are located within three countries: Spain, France and Italy. Germany, in spite of being the biggest economy in Europe, holds the fourth position. Under an assumption that each of the GLs owns one coffee machine, the ratio of espresso machines to the national population is presented in Figure 2-2. Bearing this in mind, one can point out a strong regional differences between particular nations: for example Greece and Portugal have ca. 3.5 times more espresso machines per capita than Germany, which aligns well with Nobly's Europe's Biggest and Smallest Coffees Cultures [25]. It is remarkable and unintuitive a fact that France has proportionally the lowest quota of machines.

The economic activity data can be confronted with 2019 sales results. The Figure 2-3 presents most vital information from HKI. It describes the distribution of coffee machine in sales according to machine's

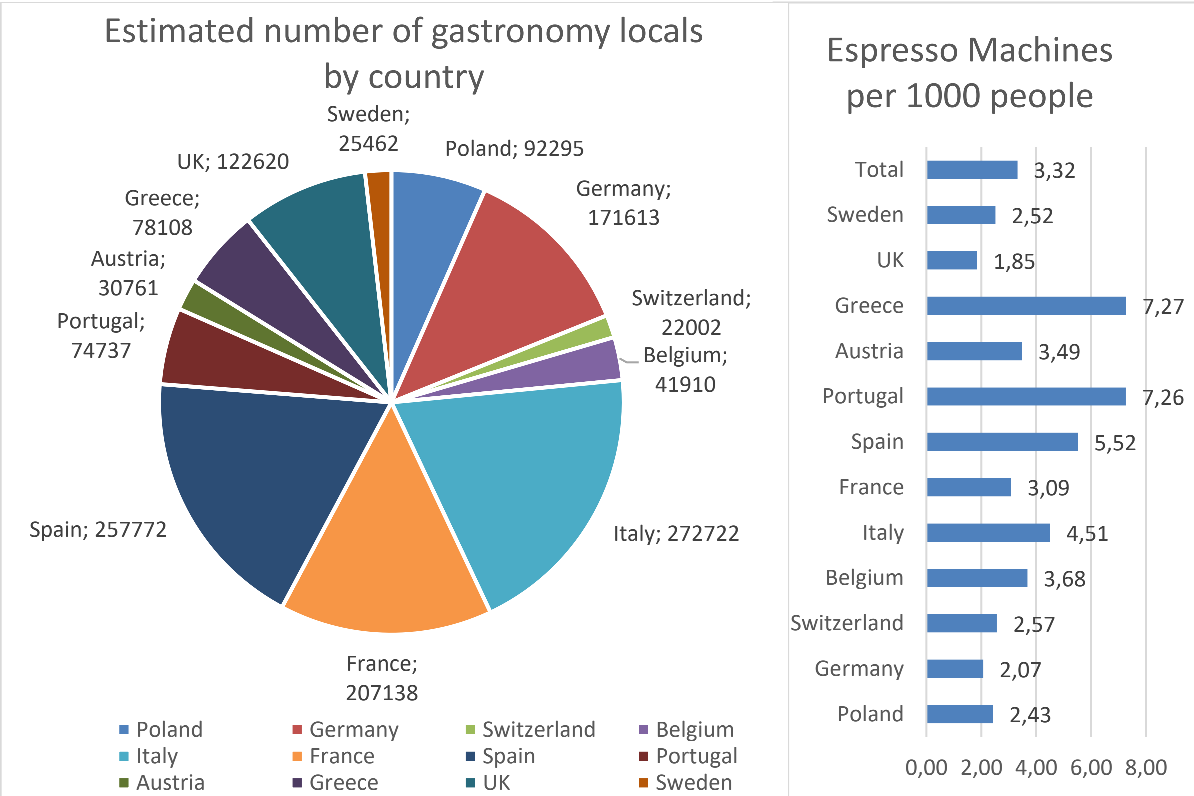

Figure 2-2 Data analysis outcome: Gastronomy locals on national levels in accordance to NACE 561 Restaurants +563: Beverages establishments (2017) (left side) and number of espresso machines per 1000 people (right side)

type. Firstly, the data is divided into two main categories: automatic and traditional machines. Furthermore, they are subdivided by price category and number of spouts, respectively. The data reveals a significant difference between the ratios of automatic to traditional machines. Four countries, namely Greece, Portugal, Spain and Italy, purchase mostly traditional machines (60 - 70%). On the contrary, Belgium, Germany, Switzerland and Austria follow the trend of interest in automatic espresso machines. It corresponds with the fact that within these countries the most renown manufacturers of automatic machines (e.g.m WMF, Rex Royal, Thermoplan) are localized.

In the Figure 2-4 a categorization of coffee machines in terms of relevance for KOENA tec is presented. The left part of the graph depicts the less optimistic scenario. In this case only three and four group machines are counted. Additionally, it is possible to notice the size of the market enlarged by addition of the most expensive (12000 euro +) automatic coffee machine. As it was mentioned previously, a few countries are creating the vast majority of the market. Only four countries (Italy, Greece, Portugal and Spain) constitute 88% of the traditional 3 and 4 group machines' market. Out of these four, Italy alone is responsible for more than 50% of market value. On the contrary, the group of Sweden, Belgium, Switzerland and Austria possess less than 1% of relevant appliances. These proportions of various countries change slightly when automatic machines are taken into consideration. Although Germany, Sweden and Austria increase their stock size a few times, the addition of automatic appliances does not change the positions of market leaders.

On the right side of the table, the forecast for more optimistic scenario is shown. The quantities of 2, 3 and four group machines are displayed. Their values can be adjusted by the addition of automatic coffee machines (8000 euro+). In comparison to the left part of the table, the inclusion of the 2nd group of traditional machines significantly widens the targeted market. Only in Italy it means additional 110 000 of appliances, whereas the stock of Spain increases several times up to c.a. 160 000. In total, the size of the market raises from about 140 000 to nearly 520 000. Similarly, if one takes into consideration that the automatic part of appliances enlarges the quantity of machines even more.

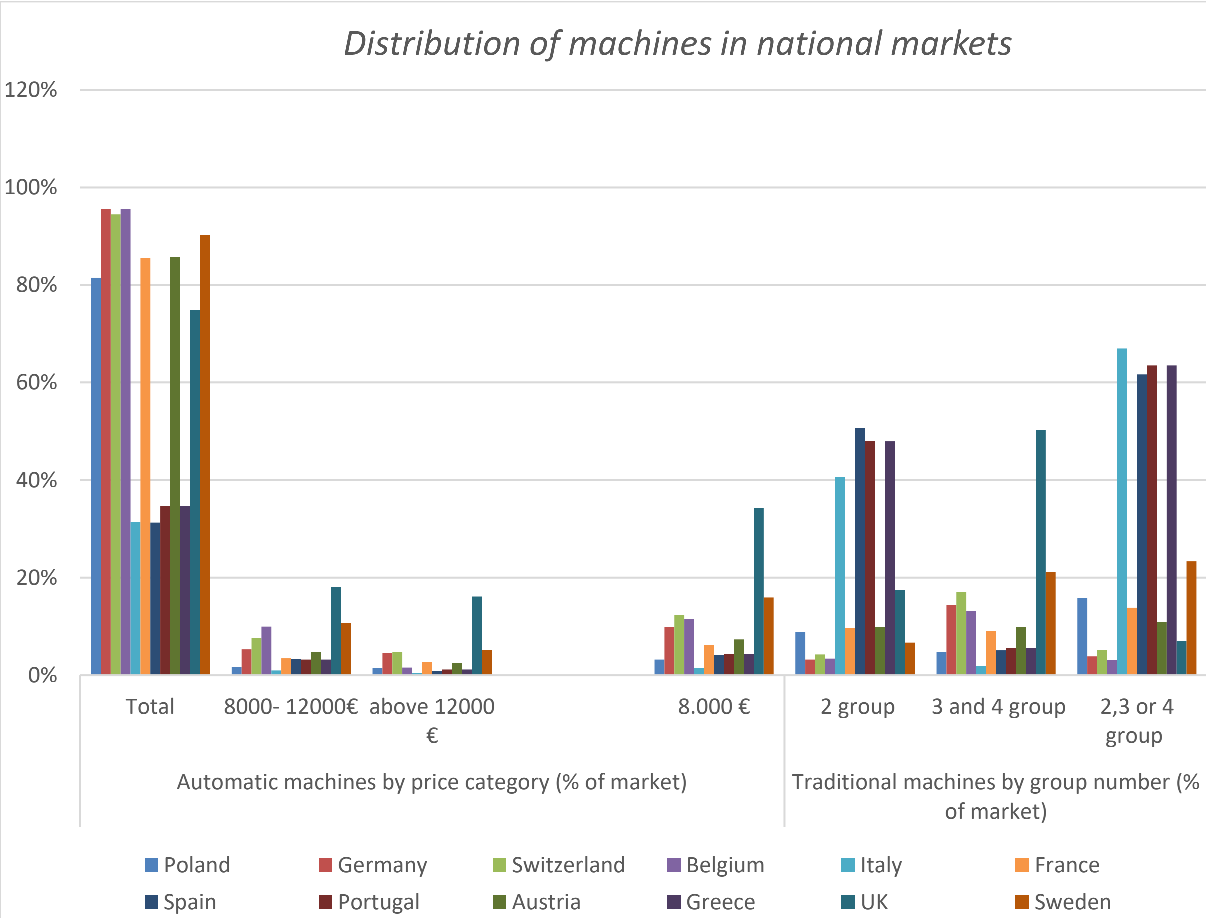

Figure 2-3 Distribution of various kinds of coffee machines in sales in 2019.

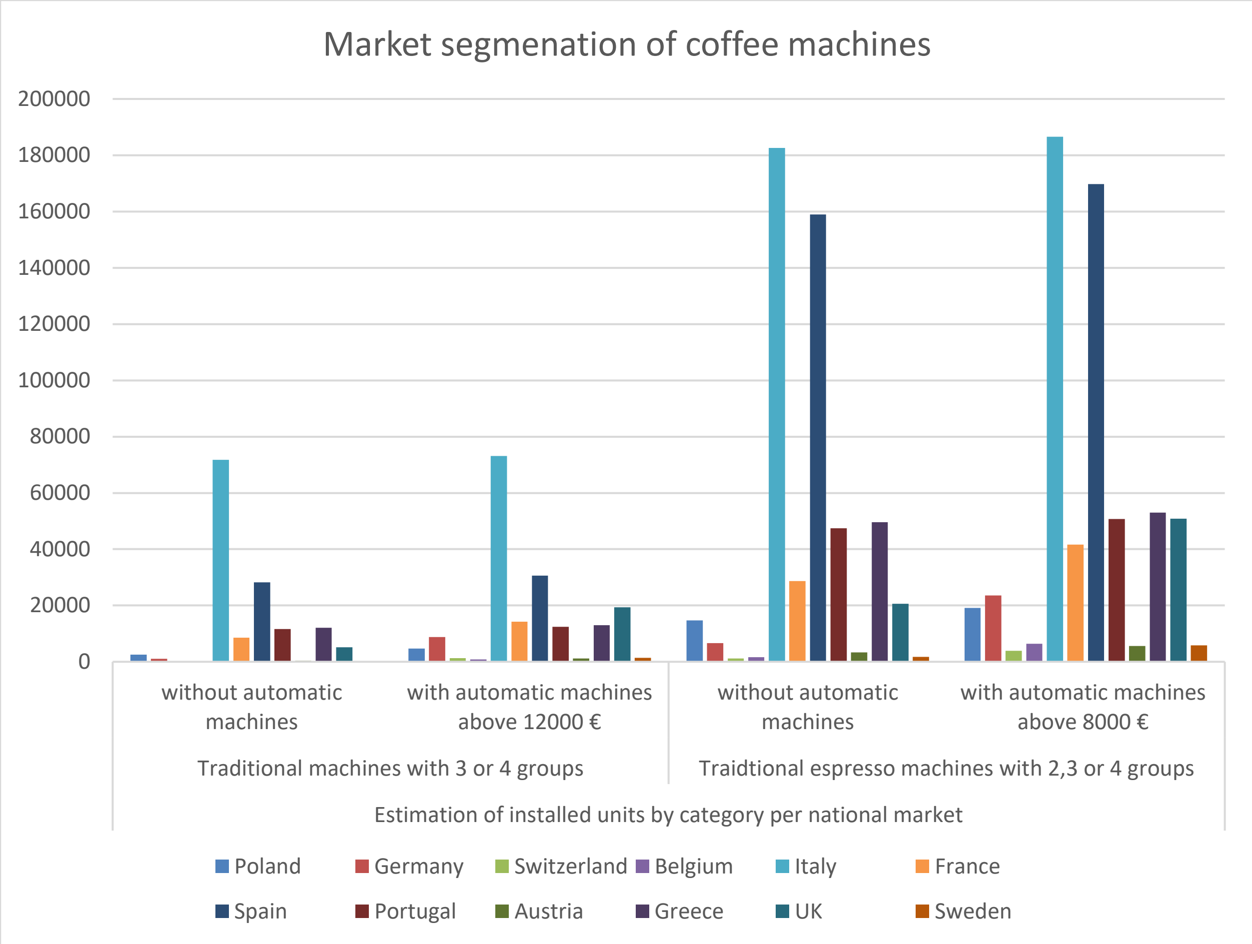

Figure 2-4 Installed units of coffee machines per country. Categorization of data based on groups (in the case of traditional machines) and by price (in the case of automatic ones).

There are, however, some doubts concerning the results presented above. For instance, one can have a look at an interesting case of Poland and Germany. Since both countries are situated in a similar geographical and cultural area, major differences between them are the level of wealth and size of population. The number of Germany's inhabitants is accounted for twice as many as Poles, and German GDP exceeds Polish one around 8 times. Consequently, it would be reasonable to assume that Germany possesses a much higher number of appliances. This is, however, false in the case of traditional machines, as here Polish market is about 2.5 times bigger. Surprisingly, even with the addition of automatic appliances, Germany's values are not much bigger than the Polish ones. Similarly, the number of traditional machines in Greece and Portugal, although both famous for their coffee culture, seem to be overestimated. Especially if one compares them with France, a country with a population 6 times more numerous but having lower quantity of traditional machines.

These probable underestimations of Germany and France as well as overestimation of Portugal, Greece and Poland might be a result of the applied methodology. There are a few factors worth considering. First of all, the assumption of associating one restaurant with one coffee machine should probably differ among countries. Secondly, there might be some discrepancies between application of NACE system by particular countries. Last but not least, it is also likely that distribution of coffee machines in countries' stocks are not identical with distributions of sales volumes. Especially that the sales data sheet concerns only one year of data, which can be strongly affected by seasonality and trends.

Chapter 3

Energy Efficiency Opportunities

In the third part of this research, energy efficiency opportunities for coffee machines are presented. Subchapter 3.1 includes a brief introduction to the problem, whereas the proposed methodology is discussed in section 3.2. The data obtained from investigated coffee machine is analysed in section 3.1. At the end of this part potential energy savings are demonstrated.

3.1 Introduction and Objectives

The main goal of this analysis was to investigate possible areas where energy consumption can be reduced. Bearing this in mind and taking into consideration the need to preserve the quality of coffees delivered to restaurants' customers, it is important to point out that potential savings cannot include the energy required by the process of making a proper coffee. They should, instead, focus on the energy loses, mainly on undesirable heat loses from tanks. The general heat equation consists of four parts: conduction, convection, radiation and heat from mass transfer[26]:

$$q = q_{conduction} + q_{convection} + q_{radiation} + q_{mass\ transfer} \quad (6)$$

The scope of the following analysis focuses only on the heat exchange between boilers and environment (losses through heat convection) and consequently the heat from mass transfer can be omitted. Furthermore, radiation heat is so small that it can be considered not relevant. As we do not possess sufficient knowledge about the geometrical and material characteristics of the espresso machine, and in order to avoid solving a challenging heat transfer equation, it is assumed that q can be related with both ambient and boiler temperature with a simplified mathematical notation[26]:

$$q = a\Delta T \quad (7)$$

where q – heat flux [Wm^{-2}], a – convection parameter [$Wm^{-1}K^{-1}$], ΔT[Km^{-1}] – difference between boiler temperature and ambient temperature.

Assuming that the ambient temperature and the parameter ***a*** are constant, it can be concluded that heating loss depends only on the boiler temperature. Consequently, maintaining steady temperatures by simple thermostat or PID controller for periods were coffees are not made, seems to be a waste of energy. Thus, it would be interesting to estimate such a value, which would describe energy losses due to a non-optimal heating algorithm. This can be done through a comparison to a perfect, theoretical heating cycle, which would deliver energy to tanks immediately before each coffee is made. While it is not feasible to anticipate the time for each cup of coffee, the described methodology allows to estimate a useful optimal upper bond in energy efficiency. This approach will be addressed more deeply in subchapter 3.1.

On the other hand, a more pragmatic approach would be of importance. Previous discussions with bar & restaurant owners indicate that during some periods of a day, coffee machine is operating with much lower frequency. Thus, the second methodology will focus on comparing various weekdays and investigate possible time patterns. This approach seems to be much more pragmatic and opens the way for direct advices for the entrepreneurs.

3.2 Proposed Methodology

Unfortunately, available data does not include direct information neither about energy used for making a coffee nor its timestamp. Due to this obstacle, a methodology was developed in order to infer this from the load profile of the machine as follows:

1. distinguish between power consumption for a direct coffee-making process and keeping temperature of both boilers steady,
2. examine when a coffee is being made,
3. measure and infer how much energy can be saved on heating cycles.

The basic schematic of the algorithm is presented in Figure 3-1. According to this figure, energy dissipated between boilers and environment is considered a loss, whereas direct energy consumption for product preparation is the main function of coffee machine. A day cycle can be described as a combination of two elements: a night cycle and a heat cycle, which is due to brewing coffees

For the purposes of this chapter, it is vital to establish a distinction between two functions of boilers' heat cycle:

1. to recover losses due to heat transfer between boiler and environment, and
2. to compensate for the heat precipitated during the coffee-making process.

As mentioned, the energy consumption related to the direct coffee brewing should not be concerned as a loss and, consequently, is of a lower importance for this thesis (Figure 3-1). In order to investigate the first function of boilers, a night heating cycle has to be addressed, since no coffee is made during this period.

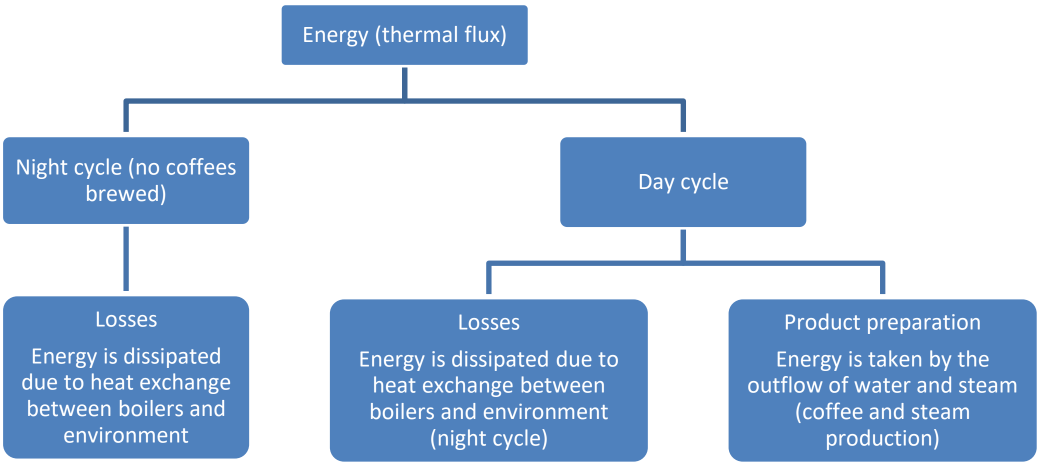

Figure 3-1 Graphical presentation of components of thermal flux.

Two separate functions were created to identify heating periods for both steam and coffee boiler. It was then possible to calculate the energy delivered for the night reference period (12:20 AM to 5AM) for each boiler. The following parameters were obtained: μ_{coffee_boiler} and μ_{steam_boiler} describing an average energy loss per second for a night heating cycle. A question which should be addressed is whether those parameters can be used effectively to describe heat loses during a daytime, when a coffee-brewing process impacts the temperature distribution. As the temperature control devices follow the same algorithm during night time and day time, the mean temperature should also remain similar, such an assumption should be reasonable. Thus, the heating loses per day can be calculated as follows:

$$heat\ loses_{day} = \mu \cdot time_{day} \quad (8)$$

Where $time_{day}$ is the length of the daytime.

$Heat\ loses_{day}$ then characterize how much energy is dissipated for heat during the day [8:00 AM to 9:00 PM] with current heating algorithms. According to the equation (6) and (7), the amount of energy can be reduced by decreasing the boiler temperature. Theoretically, this would be possible with a boiler preheating just before a coffee is being made. To estimate this potential saving, it is necessary to obtain the timestamps of each coffee brewing and calculate heat transfer between them.

Since an old version of KOENAs' measurement box was used to obtain the consumption data, no information about brewing times is delivered. The idea to identify coffee distribution with a pattern of energy consumption is tempting, but unfortunately, futile, since the energy consumed to produce a coffee unit is not constant. It happens because baristas might set various brewing times whereas an espresso machine offers more than one sort of drink. It turns out to be a necessary step to design another simple and reliable algorithm. In this case, the solution is to look for correlations between the pump use and coffee brewing process. In fact, the pump consumes power when high pressure is needed to push water through tightly filled portafilter's basket of ground beans. Adopting this approach made it possible to identify timestamps for coffee units.

To estimate how much energy can be saved in a situation that all coffee demands can be anticipated, one has to subtract the energy needed for a perfect heating system from heat $loses_{day}$: $heat_{theoretical}$ (Figure 3-2 – last chart's puzzle).

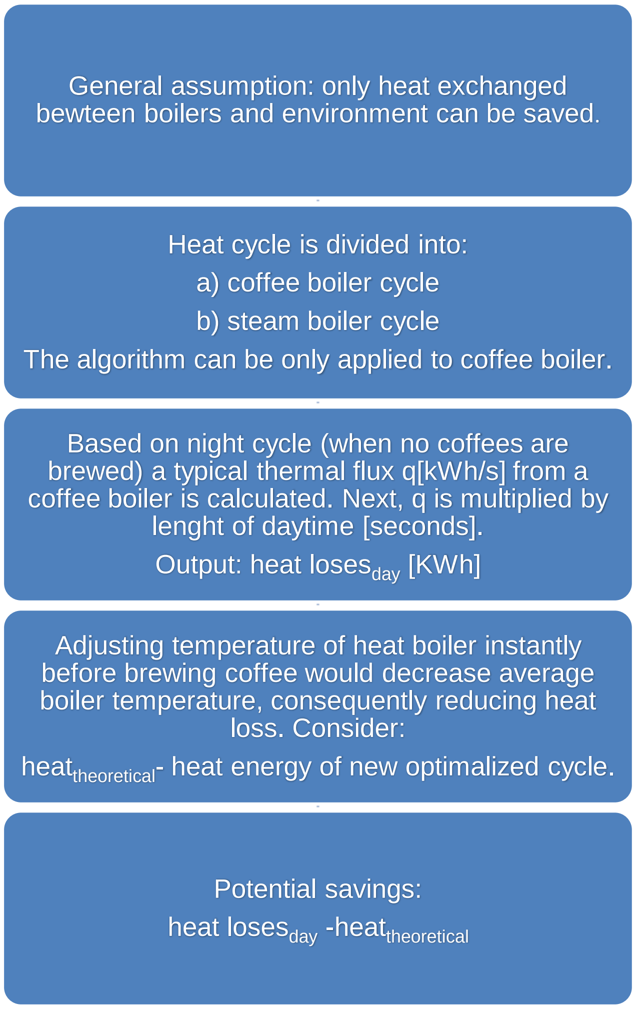

Figure 3-2 A graphical representation of applied algorithm.

To validate heat transfer between brewed coffees, two elements are necessary: a data frame with the amount of time between each coffee that is being made, and the parameter ***a*** from equation (2).

It was already mentioned how to obtain temporary data for coffees. In case of the parameter *a*, the following algorithm was used. During night-time, an average time avgtime$_{coffeboiler}$ and energy avgenergy$_{coffeeboiler}$ of a coffee boiler heating cycle was calculated. A ΔT caused by heat dissipation is computed from the following equation:

$$Q = c_{p\,water} \times mass_{water} \times \Delta T \tag{9}$$

Assuming that c_p=4.19 kJ/kgK, water mass= 5kg and obtaining Q by summing energy delivered during avgtime$_{coffeboiler}$ a ΔT is known. Subsequently, it is assumed that thermal flux *q* is constant in time and parameter *a* can be calculated from (7).

To estimate value of heat$_{theoretical}$, the following algorithm is in use. First of all, it is assumed that whenever a coffee is being brewed, temperature raises to a reference value of 93.3 °C. Afterwards, the thermal flux is calculated between each of the coffee units. In order to consider changing its temporal changes, a temperature is iteratively adjusted according to dissipated heat and formula 4.

Unfortunately, this methodology can be only applied to the heat boiler. In case of the steam boiler, the heat transfer theory cannot be analogically simplified because the process parameters indicate possible phase transitions and, consequently, constant temperature during heat transfer.

3.3 Available Data

In cooperation with one of the partners, preselected café in Stuttgart, KOENA tec. collected data from two 3 group coffee machines. This particular café is an independent average-sized, urban-style café & bar serving hot and cold beverages, snacks and drinks. It is open seven days per week from 8 AM to 11 PM except for weekends, with operating hours till 1-2AM. The café owns two fully working espresso machines *La Marzocco Linea Classic* model EE (Figure 3-3). A coffee machine consists of five main elements: water boiler, coffee boiler, exterior, three brewing groups and pump[27]. The first two are of special interest due to their heat storage function. The steam boiler's main part is a cylindrical tank made of stainless steel whose recommended operational pressure is 1.5 bar. Effective volume and standard power rate are 11 litters and 3 kW, respectively. The coffee boiler, on the other hand, has much higher operating pressure equal to 9 bars and effective volume of 5 litters. The suggested temperature for making coffee corresponds to 93.3 °C and is maintained via PID controller with a dT of ± 0.5°.

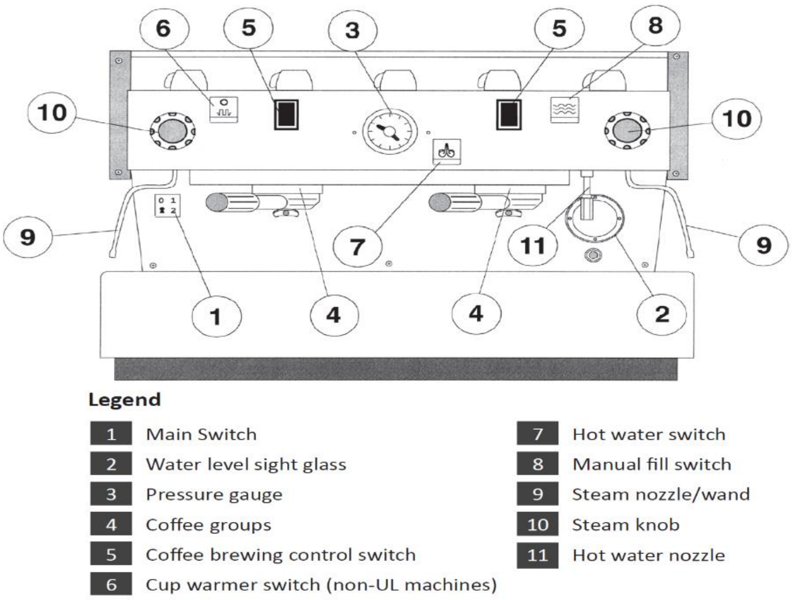

Figure 3-3 A scheme of La Marzocco coffee machine[27]

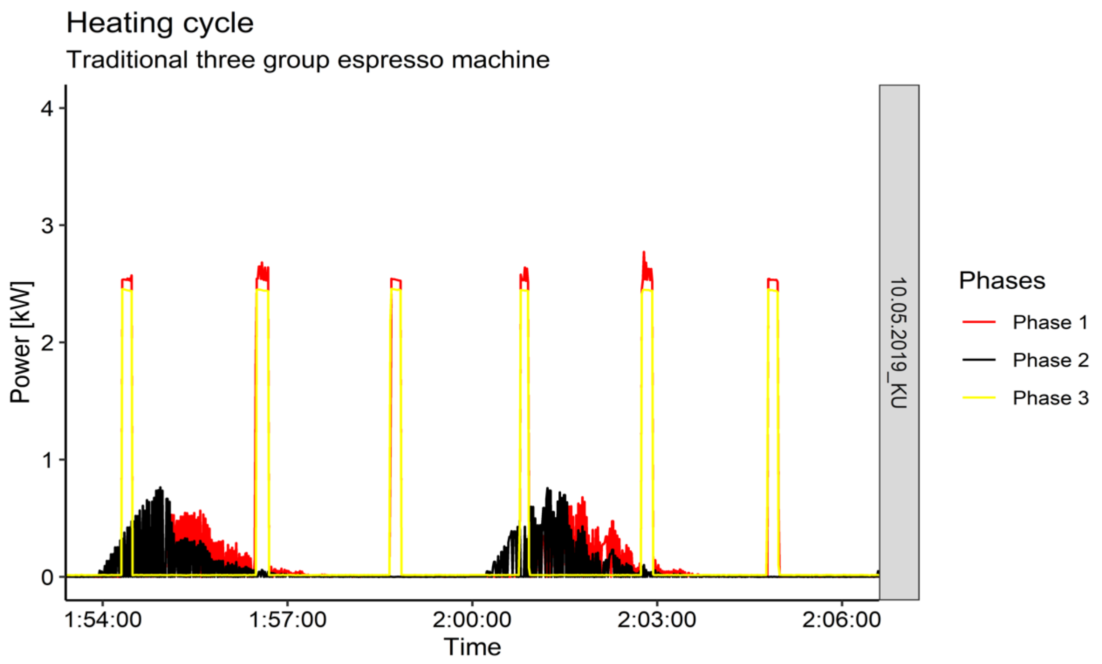

Figure 3-4 Heating cycle of a coffee machine.

The espresso machine was connected to one of the KOENA tec's measurement boxes from March 2019 till March 2020. Due to technical reasons and scope of the research question, it was decided to consider the period of three months from 1st October to 31st December 2019 as a reference period. KOENA's device collects power values from each of the three phases in seconds resolution and continuously transfers them to main server. The phase connection to the electrical elements is the following: 1 phase – steam boiler and coffee boiler, 2 phase- coffee boiler, 3 phase- steam boiler and a pump. An exemplary plot is presented in Figure 3-4. Periodical, rectangular high peaks reflect the power use for preserving heat in a steam boiler (colour red & yellow), whereas more flattered, uneven periodic rises show PID controlled heating for a coffee boiler (colour black& red). Since no coffee is made during night, the pump's power consumption is not presented in the graph.

3.3.1 Data Pre-processing

The data used in this research was collected by KOENA tec measurement box. The device was yet of the older generation and, as its consequence, within the obtained data there are some missing values. Due to the capacity of the server, it was only possible to download data separately for each of the days. Let us investigate the structure of a particular single day, i.e. 5th October 2019. The data record consists of 76696 instances, which corresponds to 89% of the timestamps in 24 hours. Furthermore, 175 of 76696 instances have a duplicated timestamp. It is possible that the device measured the phases' power twice within a given second. However, these observations will be considered as duplicates and will be deleted.

Moreover, it is important to investigate the missing values of phases' powers. The percentage of missing values for each of the phase was calculated. The results were structured and they are presented in the

Figure 3-5, It can be noticed, that slightly more than 4% of the first phase values are missing, whereas this ratio is equal to 3,5% for the second and the third phase. Furthermore, the right side of the Figure 3-5 shows how these missing values are corelated, i.e. it presents the percentage of all possible combinations of missing values within dataset. 91 % of all available data include values for all the variables, whereas only 0,38% of instances have missing values from all three phases.

It was decided that the missing values characterised by random occurrences would be replaced. Different methodologies were discussed, however, a simple approach of replacing NANs with the most recent non-NAN value prior to them was chosen. It seems to reflect very well the behaviour of the appliance's load, because the particular elements of heating cycle (such as pump's operational time, steam and coffee boiler heating phase) have a time length longer than one second.

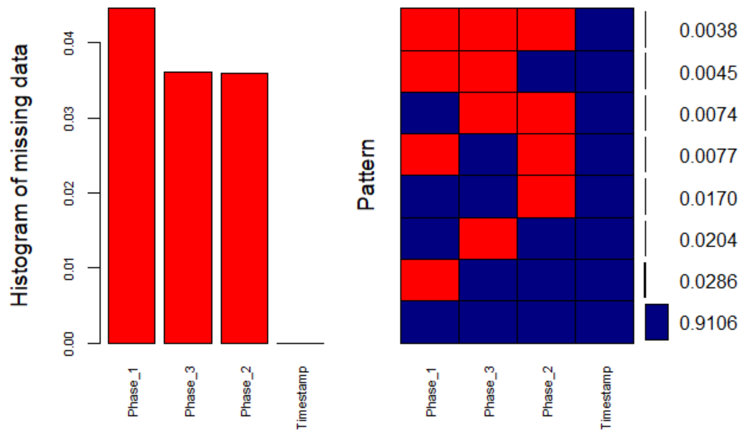

Figure 3-5 Graphical presentation of missing values in a single day of data (5th October 2019).

3.4 Results and Discussion

Following the methodology described previously in chapter 3.2, this part of the thesis focuses on the issue of energy efficiency in coffee machines. First of all, it is important to point out, that an increase of energy efficiency is only possible, when one considers heating loses between boilers and the environment. The energy consumed for product preparation should not be treated as a loss. Consequently, the heating cycle of both steam and coffee boilers have to be investigated.

As it was mentioned previously, the thermal flux depends on the temperature of the source and

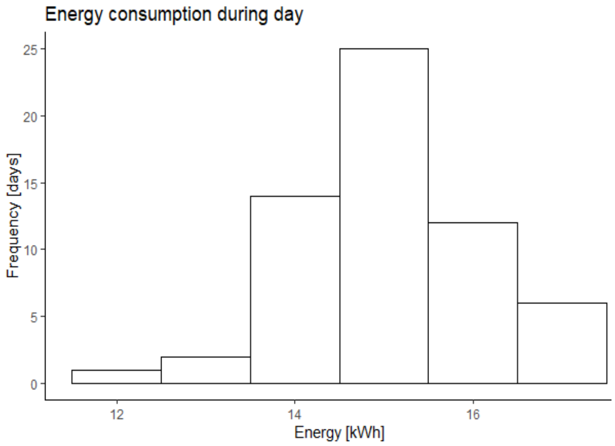

Figure 3-6 Distribution of energy demand during days (8:00 AM to 9:00 PM)

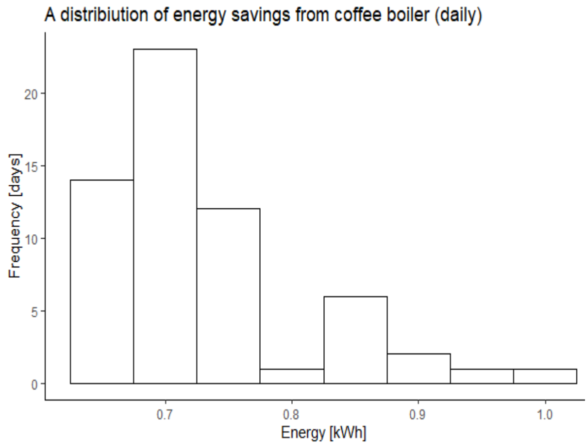

Figure 3-7 The distribution of energy savings per day based on coffee boiler

environment. Theoretically, introducing a new heating cycle, which assumes switching on the heating up phases instantly before brewing coffees would decrease the mean temperature of boilers, consequently reducing the heat loses. Although, such solution is not feasible for typical cafes and restaurants, an estimation of upper bond of energy savings seems to be relevant. Since, the steam boiler operation process includes the state of phase transition, the corresponding heat flux is not described by a linear function of temperature. Due to the complexity of this heat exchange as well as in order not to overestimate potential energy savings, it was decided to focus only on the coffee boiler.

In our investigation we will consider a typical café with opening hours from 8:00 AM to 9:00 PM. The potential energy savings will be categorized in two groups:

1. Energy savings due to switching off the machine for night time,
2. Energy savings due to applying a theoretical heating cycle for the coffee boiler (when a boiler is heated up instantly before brewing).

Energy savings for the night time is considered to be a total power of steam and coffee boilers' heating cycle (5.76 kWh) reduced by the morning heating up phase and is equal to 4.51 kWh. Distribution of energy savings from coffee boiler per day is presented in the Figure 3-7. The average value of energy savings is equal to 0.73 kWh per day. This corresponds to a reduction of energy consumption of 266.5 kWh yearly.

Furthermore, one may observe the variation of energy consumption within days. A typical café, based on the 60 days data, would use around 15.1 kWh each day. The energy demand would be rather stable. Its distribution is depicted in Figure 3-6.

The total savings result from the combination of switching off the appliance during night and applying an optimal heating cycle for coffee machine. Their average value is equal to 5.24 kWh per day (1912 kWh per year). It is 25% of the total energy consumption.

Chapter 4

FCR Services Provision

Chapter 4 investigates the opportunity to provide FCR services. After a brief introduction to the topic a methodology is presented. Furthermore, at the end of the chapter forecasted power for FCR services is analysed. The study of disposable FCR power takes into consideration the size of coffee machine aggregation and different time intervals within a day.

4.1 Introduction and Objectives

In this section the methodology used for the estimation of potential in the FCR market is described. The approach is based on the previously defined experimental setup with a three-group professional espresso machine La Marzocco Linea Classic model EE and the data collected from it. As mentioned in subchapter 1.5, there is a large number of diverse regulations concerning the balancing market within different European countries. However, within the scope of this thesis, the focus is on two crucial factors: the direction of balancing services' delivery, and the time requirements.

For the first issue, the problem of positive balancing energy is of greater importance than the negative one. This is due to the fact that in the case of coffee machines (and any electricity using device participating in demand response) an injection of power into the grid from the perspective of a grid operator is achieved by the asset through reducing its power consumption in a given instant. Consequently, it is possible only when a coffee machine is in the heating up phase, usually when a coffee is being brewed or when the temperature control devices are switched on. Moreover, the curtailment of power use is possible unless it does not significantly impact the product's quality. On the other hand, the increase of power consumption could be readily applied within the whole operation time, but with the similar restriction to the coffee's quality. We thus assume in this analysis that "positive balancing", (i.e., a net delivery of power to the grid by reducing consumption) will be the bottleneck of coffee machines' balancing services. As for time requirements, it is important to point out that operation of power reserves should include a fast start and constant maintenance of contracted power.

Having considered the factors described above, the following methodology for the analysis lends itself well to investigating the potential of such coffee machines to participate in FCR markets. To guarantee a stable power output, i.e. constant possible reduction of energy consumption, it is assumed that a reasonably high aggregation of coffee machines might provide continuous power services. Consequently, a method to estimate the available disposable power as a function of the number of coffees machines was applied. In order to meet time requirements, a parameter t was introduced. t is defined as the percentage of time for which the calculated power is available. For the sake of this study, the parameter t was set to 0.98. Although the Café's opening hours were various, only times between 8 AM and 9 PM were taken into consideration in the analysis. This is due to the fact that the aim of this investigation is to estimate the FCR potential for a typical coffee machine based on our data as well as to avoid the issue of much different appliance behaviour during opening and closing times.

In order to obtain a more detailed description of the coffee machine behaviour, the analysis proceeds in two stages: The first part focuses on a comprehensive investigation of the La Marzocco machine's load during weekdays and daily hours, whereas the second one estimates the disposable power over all of the considered timesteps. In the latter, three different approaches are considered. The first one describes the worst-case scenario, in which no coffees are made. The second one will assume the lowest value of constant power during weekdays and hours to be the bottleneck and limiting factor. In the third approach, we divide the analysis of disposable power into daily time slots with adequate availability. The issue of product quality will be discussed separately within the results chapter.

4.2 Proposed Methodology

The first step is to analyse the impact that a particular weekday and hour have on the appliance's load. This is especially important for markets where FCR services can be provided within small time intervals i.e., different values can be contracted for different days or day periods, or even particular time blocks. On the other hand, for other sorts of markets, this approach might be beneficial to identify the bottleneck of the services.

As the load profiles are difficult to model analytically, some assumptions have to be made. First of all, the approach of associating pump work with brewing coffees will be continued. Due to the lack of additional indicators, it is not feasible to identify the exact coffee products. Therefore, it is assumed that it is possible to infer that a single coffee is produced when the pump works longer than 16 seconds. This value is slightly lower than 20 seconds, which is the usual minimum time of brewing espresso [28]. However, it reflects the histogram of the pump's working time observed in the collected data and an initial exploratory analysis of the data. This approach however underestimates periods in which many coffees are made in short succession, since even long pump's duration can account as single cup of coffee. Thus, it might be more reliable to examine the pump's total working time for given time intervals. Both approaches were considered. Results in the form of graphs are presented in the section "Results". This methodology does not take into account all of the short-time runs of the pumps, which might refer to some hot water usage and cleaning. In conclusion two approaches for inferring the number of produced coffees from power use data from the pump are applied. They are based on the following assumptions respectively:

1. Activations for longer than 16s imply one coffee made
2. Aggregation of total activation time of the pump (minus all short durations of below 15s)

The intervals for both - coffee counts as well as aggregation of pump load time - are set to 10 minutes. Based on such generated load profiles, timeslots with similar power consumption will be identified. The timeslot with the lowest load value will be treated as FCR bottleneck.

4.2.1 Data Generation

Based on data collected from 1st October 2019 to 29th November 2019 (the duration of 60 days), it was decided to create a data generator in order to simulate a larger number of coffee machines. The first step to follow this approach was to establish a method to forecast the timestamps of brewing coffees.

The vital characteristic of a coffee machine is to be able to deliver its product on-demand despite extended periods of zero-demand. An attempt to anticipate such erratic demand is ambitious and difficult, because irregular demand arrivals are combined with different demand sizes. The literature review shows that a number of solutions were discussed, as the problem occurs frequently in plenty of industries, mostly associated with stock control systems, for example engineering spares kept at wholesale warehouses [29].

J.D. Croston in his article "Forecasting and Stock Control for Intermittent Demand" [30] suggests a decomposition of the data into two independent series: the first one to be associated with inter-demand intervals and the second one to focus on the value of non-zero demand.

Many other alternatives [31], [32] based on this method were later proposed, such as Syntetos-Boylan Approximation [33] or Teunter–Syntetos–Babai method [34]. They all, however, focus on estimating an average future demand, which is not the issue addressed in this analysis.

Nonetheless, due to a similarity between coffee brewing behaviour and stock control for intermittent demand, a similar approach for data generation may be applied. Especially, addressing coffee demand arrivals and sizes separately seems to be a reasonable concept.

However, before applying any direct technique it is crucial to consider the possibility of temporal aggregation. This idea was successfully described and proofed by K. Nikolopoulos et alumni in their work "An aggregate–disaggregate intermittent demand approach (ADIDA) to forecasting: an empirical proposition and analysis" [35]. It is possible to decrease or even eliminate variance from demand arrivals by cutting down the frequency of our data. In our case, we will focus on dividing demand series into non-overlapping consecutive block of length equal to 10 or 20 minutes. Consequently, the inter-demand interval (IDI) of our data, i.e. the mean distance between demand arrivals (in our case the average time between brewing coffees), will change from around 192.206 s to 1.06 s for the middle day data.

For the needs of this thesis, the once aggregated data will not follow the disaggregate stage identically as in the ADIDA model. Although, the change of the resolution from seconds to 10 and 20 minutes intervals seems to be relatively high, it is considered reasonable. Furthermore, this approach would allow to have a clearer discussion on the results in the context of cafés, for which 20 minutes intervals should be enough to capture any daytime trends of product sales.

Another relevant issue to discuss is the selection of proper distribution for forecasting model. There have been numerous studies to investigate the goodness-of-fit of a number of parametric statistical distributions in the field of intermittent demand. The non-parametric alternatives [36], which mostly focus on bootstrapping procedures, are not considered in this thesis. A long discussion concerns the selection of a proper distribution for forecasting data. Considering the case of a discrete time variable, a Bernoulli process can generate demands, whereas for continuous time the Poisson or Gamma distribution is used. Among others, a compound Poisson distribution has been discussed among operations research scientists [29], especially while applying it along with geometrical distribution for demand size. One may also follow the widely used normal distribution [30], however it would be rather unrealistic when applied to demand sizes. Interestingly, a normality assumption can turn out to be more reasonable in case of lead time demands due to the central limit theorem's impact on the summation of demands over relatively long time horizon or when the coefficient of variation is low [37].

However, Syntetos and Boylan in their research [33] managed to develop a classification of demand distribution based on two parameters: inter-demand interval (IDI) and squared coefficient of variation

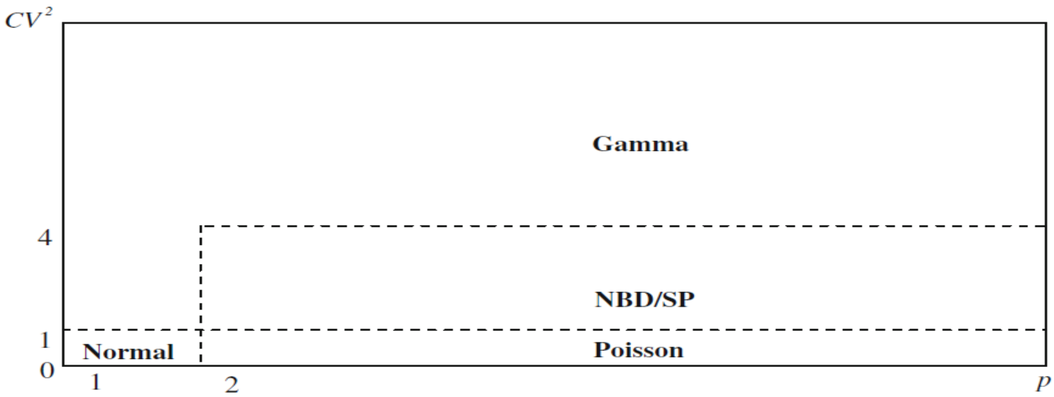

Figure 4-1 Classification scheme for demand distributions, where p corresponds to IDI

CV^2. Their empirical study resulted in the scheme presented in Figure 4-1. It can be observed that for low values of CV^2 and IDI a normal distribution is recommended. Low CV^2 corresponds generally to Poisson distribution, whereas Gamma is used for extreme cases. Negative binomial distribution seems to be a reasonable choice for other situations. Another proposed qualification scheme divides data into qualifying and non-qualifying. The qualifying one will be considered when variance is not smaller than the mean. Two distributions are recommended for them: NBD and Poisson. Similarly, based on IDI and CV^2, we can distinguish four kinds of demand [38]:

- Smooth – which occurrence has very few no-demand values and demand itself has modest variation.
- Intermittent – when there is plenty of no-demand data, but variation is not substantial.
- Lumpy – with a very high variation of demand and high occurrence of no-demand data.
- Erratic – with very few no-demand arrivals and present high variability in demand size.

In our specific case of data obtained from the selected Café, there is some variation between IDI and CV^2, depending on the level of aggregation and on a particular day. However, most often a squared coefficient of variation is lower than 1. On the other hand, as mentioned before, the IDI parameter can vary spectacularly, from values up to 200 (seconds resolution) to nearly 1 (aggregated data). Nonetheless, even for aggregated data it can obtain different values in the range from 1 up to ~8 (times between 20:00 and 21:00).

Taking this into consideration, it is a challenge to properly select the best fitted distribution for a given dataset. However, based on Figure 4-1, one can suggest that NBD or Poisson distribution should be addressed, as the gamma distribution is too extreme and the normal one does not include high IDI range. Although Poisson distribution is very encouraging, it was decided to choose negative binomial distribution due to a few reasons. Firstly, the presented qualification scheme is based on empirical studies of stock keeping units (SKU). Thus, a discrepancy between SKU and our dataset is probable. Consequently, a distribution which can be suitable for wider range of IDI and CV^2 is needed. Secondly, the NBD for low values of CV^2 can be less precise and provide more variety to our forecast. In consequence, it can mitigate the negative effect of building the prediction model on a single coffee machine.

Following the above discussion, in order to estimate intermittent distances, the same methodology will be followed as in article "Horses for Courses' in demand forecasting" by F. Petropoulos et alumni [39].

The non-zero demands are forecasted using Bernouli distribution are described with probability density function:

$$P(n) = \begin{cases} 1 - p & for\, n = 0 \\ p & for\, n = 1 \end{cases} \tag{10}$$

Where n is a possible outcome and it is equal to 1 with probability p (success) or to 0 wit probability 1-p (failure). It is a special case of binomial distribution with one number of trials. In our case the probability p is equal to the inverse of inter-demand interval:

$$p = 1/IDI \tag{11}$$

This creates a binary vector B of given length l. The actual size of the demand (number of coffees made when demand is non-zero) is calculated using the negative binomial distribution [29], [39], with given probability density function:

$$P(X = k) = \binom{k + r - 1}{k} p^r (1 - p)^k \tag{12}$$

Where, k is number of failures, r is equal to number of successes and p equals to probability of success.

In our case:

$$n = \frac{\mu p}{1 - p} \tag{13}$$

where n is number of successes, p is probability of success and μ is the mean number of coffees per interval. And:

$$p = \frac{\mu}{C_v^2 (1 + \mu)^2} \tag{14}$$

where C_v^2 is the squared coefficient of variation.

The values generated with the negative binomial distribution are directly increased by 1 to avoid demands of zero and create a vector C. Then the output vector X_t:

$$X_t = B_t \cdot C_t, \qquad t = 1, \ldots, l \tag{15}$$

Since we are in possession of data from only one coffee machine, in order to generate power distributions for *n* other coffee machines, new values of IDI, C_v^2 and μ have to be provided. They will be based on selected coffee machine data. Each day is considered to be a single vector of length equal to the number of time intervals with values representing number of coffees. Then, a matrix 60 x 3 is created, which consists of IDI, C_v^2 and μ for each of 60 days. Parameters C_v^2 and μ are assumed to follow a normal distribution from the collected data, which seems to be reasonable due to their respective histograms. It was, however, much more difficult to find a proper distribution for IDI data. Although the author tried to fit univariate parametric distributions to our data with the help of *fitdistrplus* R package [40], the results were not satisfying. Thus, it was decided to generate new IDI values with a sampling method.

The next step will be to disaggregate these data into seconds resolution timeframe. For the sake of simplicity, it is assumed that coffees are brewed within their time intervals according to uniform distribution. Consequently, the output result will be a vector D of length 86400 with binary values:

$$D_i = \begin{cases} 0 & when\ brewing\ does\ not\ start\ at\ givent\ time \\ 1 & when\ brewing\ starts\ at\ given\ time \end{cases} \tag{16}$$

It is important to point out one more time the underestimation of coffee counts with this approach. It happens due to assigning pump's phase with any length as a single coffee. This issue will be however addressed with generating the time of the pump's work. The value of pump's working time will be sampled from all available data for each coffee. With this step, a vast majority of information is preserved in the generated data. Lastly, it is also crucial to note that for these calculations the author used a *tsintermittent* [41] R package prepared by N. Kourentzes and F. Petropoulos.

Nonetheless, the distribution of coffee counts does not describe the power distribution. Thus, it was relevant to determine a method to reflect heating cycles of coffee and steam boiler. In case of a steam boiler, power consumption can be considered constant. On the other hand, the coffee boiler's power use, controlled by PID, failed to be described analytically. This is mostly due to unregular behaviour of the heater. Not only the length of heating phases varies strongly as a function of heat losses and coffee brewing, but also its shape is diverse. A single heating phase has rather a trapezoid curve with about 40% of points with 0 power consumption.

Consequently, another approach was investigated. Firstly, it was observed that each phase is boxed in around 380 second bins. Each such cycle includes a duty-on and off phase. As the heating cycle depends on the number of coffees brewed, it is also a direct function of the length of the pump's work (which follows the assumption of associating pump with coffees). Thus, all the heating phases of a coffee boiler within 60 days were organized in a list structure with two hierarchical levels. The first level of the list reflects the length of the pump's work, whereas the bottom level includes all heating cycles with the respective pump's length of activation. Thanks to a relatively large amount of data (60 days), a sufficient number of cycles for the vast majority of possible pump activation durations was prepared. In the next step of our methodology it will be possible to directly associate a pseudorandom power distribution with any given length of activation of the pump.

4.2.2 FCR Algorithm

After an explanation of the main idea of the methodology and description of data generation, it is time to shortly present an algorithm which calculates disposable power as a function of the number of aggreated coffee machines. The input of the algorithm consists of **d** number of coffee machines, the level of accuracy, database of coffee boiler's power distributions and forecasted matrix of coffees with assigned pump's working time. The level of accuracy is the percentage of time for which a calculated dipsosable power is available, which is set to 98%.

For each of the d coffee machines the algorithm divides into two stages. The first one focuses on the coffee boiler, whereas the second on the steam boiler. It is assumed that pump's consumption is negligible in comparison and is ignored in this analysis. Each of the stages is built on night heating cycle, i.e. the cycle when coffees are not made. The on-on duty time is when a coffee boiler is switched on and off-duty when it is switched off.

In case of a coffee boiler, the first step is to establish an initial start point. It is set to random value with range of average off-duty time +/- 10%. The length of on-duty cycle is calculated respectively: 90-110% of average value. Consequently, for each cycle a $start_i$ as well the $start_{i+1}$ are known. Then pumps' operation times between both start points are summed, which corresponds to the total pump's operating time between $start_i$ and $start_{i+1}$. Then, from a database of power distributions, a random one corresponding to given pump's length is selected and copied in the middle of the cycle. In rare cases, where respective power distribution is missing, the algorithm takes a distribution from lower pump's operating time and automatically increases the pump's time of the next cycle. This might happen for situation when a pump is working constantly for more than 200 seconds, i.e. where plenty of coffees were brewed at the same time.

The next step requires paying close attention to the steam boiler. First, a power consumption due to heat loses through tanks walls will be considered. It corresponds to the steam boiler's night cycle. Thus, such a cycle, based on five hours of night data, will be projected. Similarly, as in the previous step, all time steps will be associated with mean values randomly adjusted with 10% margin. It is beyond the scope of this analysis to model the connection between the steam boiler's power use with coffee production.

Consequently, it is assumed that 50% of coffees require steam. For randomly chosen 50 % of coffee counts, we will adjust the projected steam boiler power to the pump's operation time. This correlation results from the average value of steam power per pump's time in given previously discussed 20 minutes intervals. Such value will be doubled in order to recompensate total energy loses from the assumption that only half of the coffees use steam boiler. Furthermore, an adjustment is added to avoid overlapping between the on-duty cycle of steam boiler (when it is simultaneously switched on due to no-coffee cycle and because of coffee brewing), so that maximum power does not exceed 10 kW. An example of forecasted data for a single coffee machine is presented in Figure 4-2.

Later, power distributions from both coffee and steam boilers are combined, and a full power distribution is prepared. Subsequently, the estimated available disposable power is calculated as:

$$P_{disposable} = k\ \%\ quantile\ of\ power\ distribution \quad (17)$$

where k=0.02. The function then loops through **d** number of coffee machines and prints the graph of disposable power as a function of d espresso machines.

In order to guarantee the precision of algorithm, the distribution is projected on the time of 8 hours. Depending on the input parameters the algorithm can estimate the power in given time intervals. For example, to determine disposable power for period X, input daily data should be cut to the same X period. This approach will be used to describe available power for FCR for selected time frames.

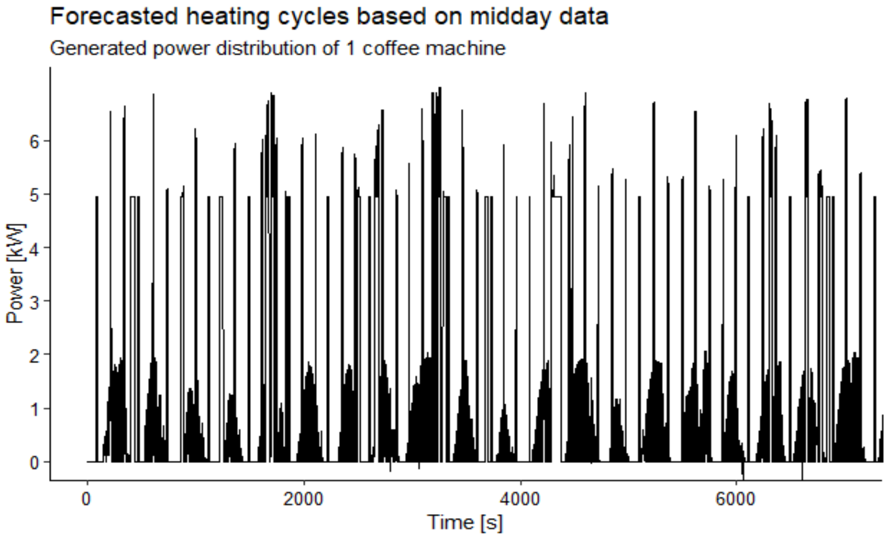

Figure 4-2 Example of power distribution generation based on data from 10:00 AM to 18:00 PM.

4.3 Results and Discussion

One of the goals of this thesis was to estimate market potential of espresso coffee machines in the area of providing balancing services. In order to do that, it is necessary to discuss the feasibility of a coffee machine to participate and offer flexible power. The approach here was to do this by analysing the machines' simulated electricity load profiles. As it was mentioned before, the load profile of investigated appliance is very lumpy. A machine consumes power only when the heating is switched on. This can happen only in two situations: when a coffee is brewed or when control devices measure temperature decreases due to thermal flux. It is additionally divided into separate control systems: coffee boiler controlled by PID and steam boiler controlled by thermostat.

Consequently, the power load can be described by on-duty and off-duty time, whereas even during the actual heating phase, the load is not very stable. Because of that, the methodology described in previous section was applied. First, the coffee machine's dependence on particular weekdays and hours is shown. Second, for selected time intervals the disposable power of multiple coffee machines will be calculated.

4.3.1 Load profile of a coffee machine based on particular weekdays and hours

This particular Café operates throughout all the week with various opening hours. Thus, it is relevant to investigate the impact of particular weekdays and hours for the load profile of a coffee machine. The analysis will be of help to identify a bottleneck of appliance's power consumption. Furthermore, for auxiliary service markets, which allow shorter time blocks for participants' bids, it will suggest a potential available power within particular time intervals. Two different approaches are presented to investigate the impact of time intervals for the load profile: the count of coffees brewed and the operation time of the pump.

In Figure 4-4, a distribution of produced coffees is presented. The data is divided into separate weekdays, such that any kind of patterns within a week can be observed. Only the timeframe between 8 AM and 9 PM is depicted, since no coffees are brewed at night time. Furthermore, mornings and evenings are characterized by various fluctuations, because of switching the appliance on and off respectively. The presented values of coffees brewed are obtained by calculating the averages for a particular weekday. Consequently, 60 days of data guarantee at least 8 days of data for each of the weekdays.

In the Figure 4-4 a similarity between all the weekdays can be observed. Only Friday, due to different opening hours, has a flat curve from around 8:00 AM to 10 AM. Apart from Friday, all weekdays have a morning increase in coffee production. It is however difficult to indicate the period with maximum values. Nonetheless, around 6 PM the demand for drinks is decreasing.

For better clarity and in order to avoid underestimation of brewed coffees, another graph was prepared. In the Figure 4-3, all the weekdays are depicted in single grid using various colours. On the Y axis there is an amount of time, for which the pump was switched on in given time interval. The X axis is identical to Figure 4-4 and it represents day time. Correspondingly to the Figure 4-4, the plotted values of pump's operational time demonstrate the similarity in demand from Monday to Sunday.

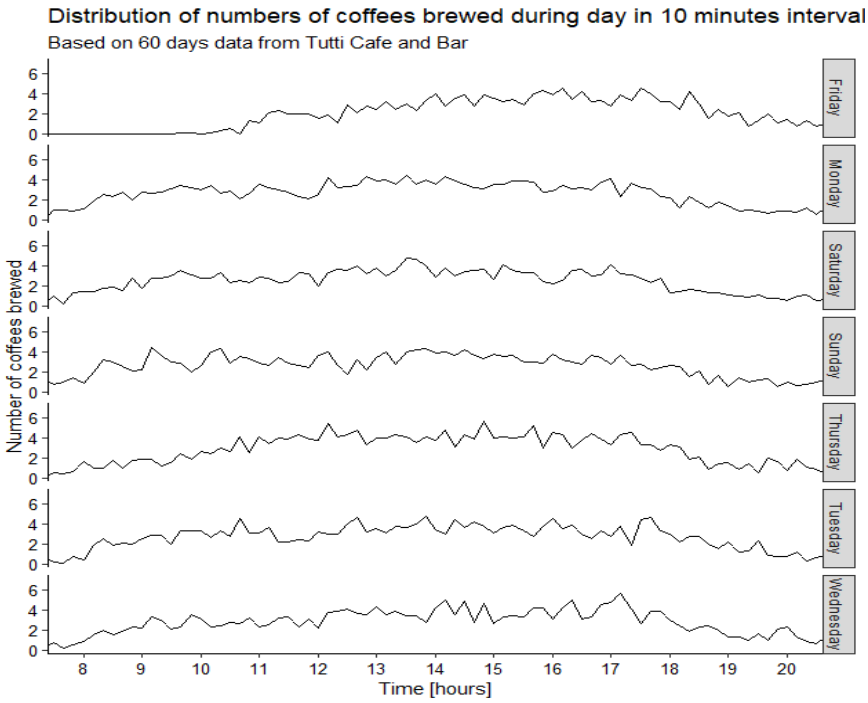

Figure 4-4 Distribution of brewed coffees within weekdays and hours.

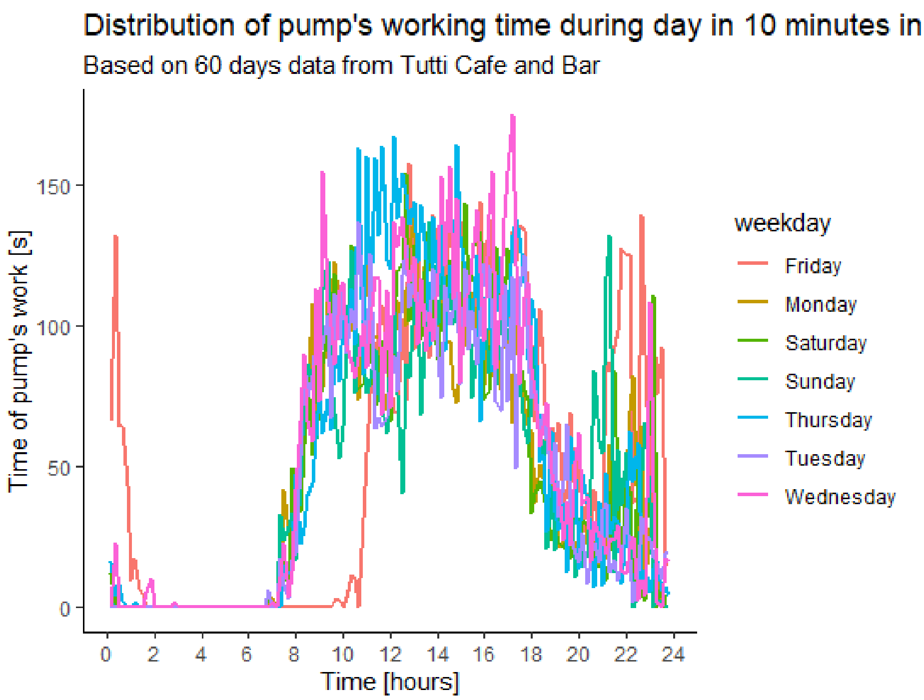

Figure 4-3 Distribution of pump's operational time within weekdays and hours. Values are aggregated in 10 minutes intervals.

Furthermore, the appliance behaviour can be divided into 5 stable periods:

1. Nighttime, when no coffees are brewed
2. Morning time (8:00AM to 10:00AM), when a rapid raise in drinks production is noticed
3. Midday time (10:00 AM to 18:00 AM), when brewing coffees is on stable level
4. Evening time (6:00 PM to 8:00 PM), when a demand is decreasing
5. Closing time (8:00 PM to 9:00 PM), the last hour of normal operation in café

Since, the disposable power for FCR services is directly correlated with coffee brewing, one may easily identify which periods of the day demonstrate the biggest opportunities for balancing services. Interestingly, based on Figure 4-3, it is very likely that for the majority of the time (10:00 AM to 6:00 PM) there is the highest achievable power. On the other hand, the last operating hour (8:00 PM to 9:00 PM) can be associated with our bottleneck time.

4.3.2 Disposable power for FCR services based on quantity of coffee machines

For all these five time periods, a disposable power for FCR services was calculated. The function of power based on a number of coffees is presented in Figure 4-5, Figure 4-6, and Figure 4-7. In all the cases, the estimation was prepared for the horizon of 100 coffee machines. The Y axis describes the power, whereas the X axis depicts the number of aggregated appliances.

Interestingly, the curve has similar shape in all the graphs, which can be divided into three separate parts. The initial, horizontal part of the curve describes the time needed to establish a non-zero power distribution within at least 98% of the forecasted 8-hour long dataset. When this condition is met, the first incremental amount of disposable power appears in the graph. Next, the curve turns out to obtain a more convex, polynomial shape. It can play a role of a transition to its third, most relevant regime.

Consequently, when aggregation level is around 25-30 a curve becomes linear. Following this assumption of linearity, it is then possible to relatively easy estimate the achievable power for any quantity of devices. The results turn out to follow the distributions of coffees and pump’s operational time from the periods in Figure 4-6. Consequently, as it was assumed the highest obtainable power corresponds to midday time, whereas the closing time is the bottleneck of our estimation. The disposable powers per 100 machines are presented in Table 4.1. The values presented in the graph are the averages of 100 different machine aggregations (100 repetitions). The confidence interval covers 95% of the results.

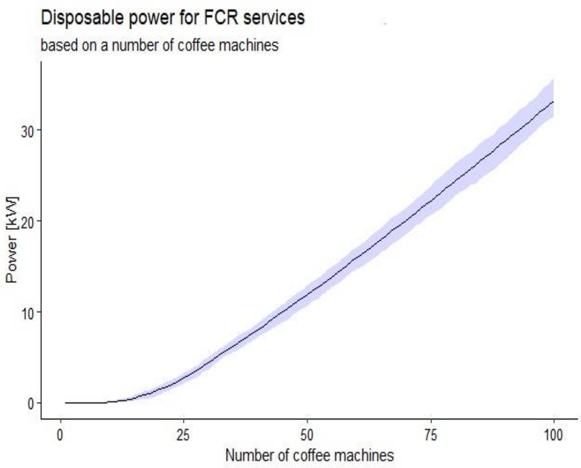

Figure 4-5 Disposable power per number of aggregated coffee machines when no coffees are brewed.

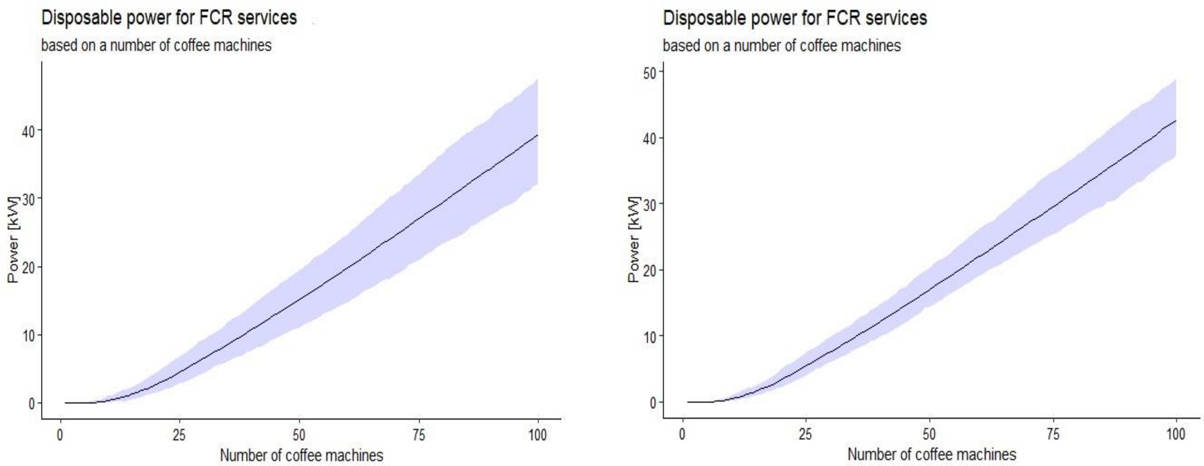

Figure 4-6 Disposable power per number of aggregated coffee machines: between 08:00 and 10:00 (left); between 10:00 and 18:00 (right).

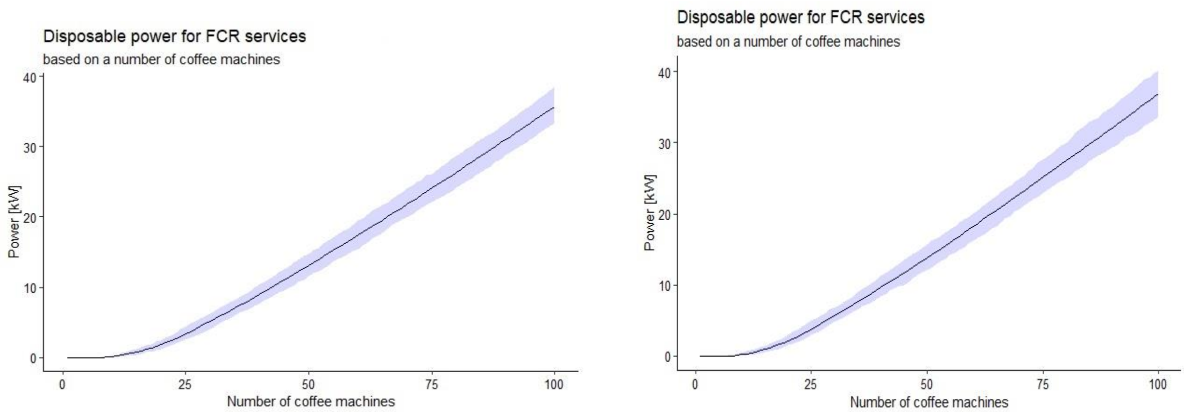

Figure 4-7 Disposable power per number of aggregated coffee machines: between 18:00 and 20:00 (left); between 20:00 and 21:00 (right).

Table 4.1 Values of disposable power per 100 coffee machines in given day periods.

Day period	**Disposable power per 100 coffee machines**
Night time	33,17 kW
Morning time (8:00 – 10:00)	39,33 kW
Midday time (10:00 – 18:00)	42,65 kW
Evening time (18:00 – 20:00)	36,90 kW
Closing time (20:00 – 21:00)	35,69 kW

Based on the assumption of linearity, the function of disposable power per coffee machine will be described analytically. The curves will be considered linear from the X=30 onwards. Consequently, five functions are created and presented in Table 4.2. Interestingly, the linear coefficient has a relatively small variance. Its difference between 'the worst-case scenario', when no coffees are made, and midday time is only 0,13. Thus, one may point out, that the majority of energy is consumed for preserving boilers in ready to use state. This, on one hand emphasizes the importance of energy efficiency discussed in other parts of thesis, but also implicates relatively low dependence of providing FCR services on behaviour of café's consumers.

Table 4.2 A table with analytical forms of functions of FCR power.

Day period	**Function**
Night time	$F(x) = 0{,}41x - 7{,}82$
Morning time (8:00 – 10:00)	$F(x) = 0{,}47x - 7{,}54$
Midday time (10:00 – 18:00)	$F(x) = 0{,}50x - 7{,}38$
Evening time (18:00 – 20:00)	$F(x) = 0{,}45x - 7{,}67$
Closing time (20:00 – 21:00)	$F(x) = 0{,}43x - 6{,}78$

Chapter 5

Results Consolidation and General Discussion

The fifth chapter of the thesis pays a closer attention to data consolidation. Collectively investigated results provide relevant insights for the whole topic of combination of energy services. After introduction and the methodology subsections, a qualitative description of the outcomes is presented.

5.1 Introduction and Objectives

In this section a recapitulation of the results concluded in previous chapters will be presented. This broader analysis can serve as a more complex and holistic approach to reflect the opportunities of espresso machines market in the upcoming energy transition process. The potential of energy savings and balancing services will be presented with regards to twelve preselected countries: Poland, Germany, Switzerland, Belgium, Italy, France, Spain, Portugal, Austria, Greece, UK, and Sweden. 7 categories for each of the countries will be considered:

- Number of espresso machines
- FCR market penetration
- Energy savings [MWh]
- Reduction of CO_2 [t]
- Savings due to energy efficiency [€]
- Savings due to providing FCR [€]
- Total profits [€]

5.2 Methodology

For the calculation of the above-mentioned indicators, the data regarding electricity prices, FCR service prices and limit of FCR was collected in Table 5.1. The aggregated results for scenario I variant a & b are presented in Table 5.2 and Table 5.3 respectively. The other scenarios are presented in the appendix. Since the estimation of the stock has been already discussed, more attention will be paid to other cumulative results. Consequently, one can indicate that for all the range of countries the market penetration remains insignificant for the scenario I. This is, however, changing together with the quantity of aggregated coffee machines. Market penetration indicator grows up to 32% for Greece and Portugal in case of scenario IVb (Appendix). Such an increase may lead to the confrontation with competitors and should be investigated further. However, that analysis is beyond the scope of this thesis.

Another relevant estimation is the forecast of CO_2 reduction. Since the carbon footprint is calculated only from energy efficiency increase, the direct values vary strongly between variant a) and b). For instance, Italy can save up to 8 times more tones of CO2 if the machines are switched off during night. Moreover, it is relevant to point out that not taking FCR services into consideration of footprint reduction underestimates our forecast The electricity price [€/MWh] are non-household values with excluded VAT tax and are collected from Eurostat [42]. The price of FCR service, considered constant for all countries, has an average value from a common market of Austria, Belgium, Switzerland, Germany, France, Western Denmark and Netherlands (The FCR cooperation) for February 2020, a monthly period before COVID-19. Similarly, the upper limit of FCR is based on the FCR cooperation database (https://www.regelleistung.net/). Exact values are collected for its members, whereas in the case of countries that have not been included, the limit of FCR is approximated.

Table 5.1 Electricity prices, FCR prices and FCR upper limits for selected countries (FCR price based on FCR Cooperation market)

Country	Electricity price [€/kWh]	FCR price [€/MW]	Upper limit of FCR [MW]
Poland	0,08	164,50	267,62
Germany	0,16	164,50	573,00
Switzerland	0,13	164,50	65,00
Belgium	0,12	164,50	45,00
Italy	0,16	164,50	426,15
France	0,10	164,50	516,00
Spain	0,11	164,50	328,78
Portugal	0,11	164,50	72,51
Austria	0,11	164,50	68,00
Greece	0,11	164,50	75,68
UK	0,16	164,50	468,15
Sweden	0,07	164,50	71,31

The reduction of CO_2 emissions is directly correlated to the energy saved and its intensity is considered to be 0,295 t per MWh, which is the average value for the European Union according to European Environment Furthermore, the study will include the 4 various scenarios of coffee machines' market estimation:

- Scenario I – Traditional professional espresso machines (group 3 and 4)
- Scenario II – Scenario I extended by professional automatic machines (price above 12000 €)
- Scenario III – Traditional professional espresso machines (group 2,3 and 4)
- Scenario IV – Scenario III extended by professional automatic machines (price above 8000 €)

Moreover, the cannibalization process of the services will be investigated. Consequently, each of the scenario will consider two variants:

Variant a) When a coffee machine is in idle mode during the night (possibility to provide FCR services during night-time, but with strong decrease in energy efficiency)

Variant b) When a coffee machine is switched of during the night (lack of possibility to provide the FCR services, but strong increase in energy efficiency

5.3 Results

The aggregated results for scenario I variant a and b are presented in Table 5.2 and Table 5.3 respectively. The other scenarios are presented in the appendix. Since the estimation of the stock has been already discussed, more attention will be paid to other cumulative results. Consequently, one can indicate that for all the range of countries the market penetration remains insignificant for the scenario I. This is, however, changing together with the quantity of aggregated coffee machines. Market penetration indicator grows up to 32% for Greece and Portugal in case of scenario IVb (Appendix). Such an increase may lead to the confrontation with competitors and should be investigated further. However, that analysis is beyond the scope of this thesis.

Another relevant estimation is the forecast of CO_2 reduction. Since the carbon footprint is calculated only from energy efficiency increase, the direct values vary strongly between variant a) and b). For instance, Italy can save up to 8 times more tones of CO2 if the machines are switched off during night.

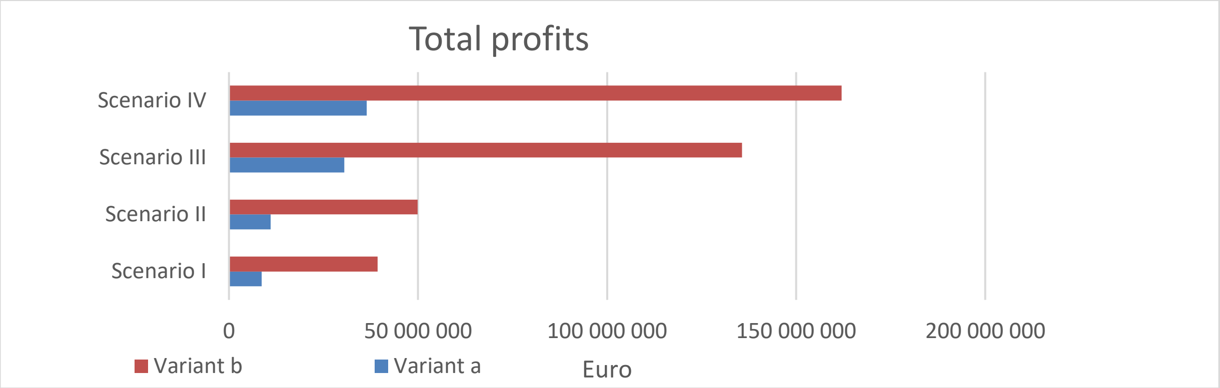

Figure 5-1 Total profits from aggregation of 100 coffee machines depending on selected assumptions

Moreover, it is relevant to point out that not taking FCR services into consideration of footprint reduction underestimates our forecast.

Nevertheless, the most significant difference, especially from an entrepreneur's point of view, is the spread between profits. In the Figure 5-1 eight various assumptions are depicted. As deductible from the table, it is conspicuous that profits are much more consequential when an espresso machine is switched off during night. Consequently, energy efficiency turns out to be more beneficial than when providing FCR services. In the best case scenario, it is possible to achieve more than 150 mln euro of revenue. Furthermore, our results demonstrated the low impact of FCR balancing services on the total profit when the energy savings measures are applied. The ratio of FCR earnings to the total revenue is set around 40%, when appliances are in idle mode during night-time and it decreases to around 5% when coffee machines are switched off.

Table 5.2 Aggregated results for traditional professional espresso machines (group 3 and 4).

Traditional professional espresso machines (group 3 and 4)

Country	Number of espresso machines	Percentage of the FCR market	Energy savings [GWh]	CO2 reduction [t]	Savings due to energy efficiency [€]	Savings due to providing FCR services [€]	Total profits [€]
Poland	2.543	0,00	678	200	56.101	62.015	118.116
Germany	1.072	0,00	286	84	45.125	25.876	71.001
Switzerland	198	0,00	53	16	6.848	4.400	11.248
Belgium	197	0,00	52	15	6.045	4.381	10.426
Italy	71.794	0,07	19.130	5.643	3.091.335	1.763.338	4.854.673
France	8.523	0,01	2.271	670	215.731	208.921	424.652
Spain	28.205	0,04	7.515	2.217	829.674	692.461	1.522.135
Portugal	11.586	0,07	3.087	911	353.457	284.168	637.625
Austria	337	0,00	90	27	9.782	7.832	17.614
Greece	12.108	0,07	3.226	952	349.720	297.006	646.726
UK	5.123	0,00	1.365	403	212.937	125.398	338.335
Sweden	89	0,00	24	7	1.646	1.730	3.376
Total	141.774	0,02	37.776	11.144	5.178.402	3.477.526	8.655.928

Table 5.3 Aggregated results from traditional professional espresso machine with 3 or 4 groups. Coffee machine is switched off for night-time.

Traditional professional espresso with 3 or 4 groups (coffee machines switched off during nights)

Country	Number of espresso machines	Percentage of the FCR market	Energy savings [GWh]	CO2 reduction [t]	Savings due to energy efficiency [€]	Savings due to providing FCR services [€]	Total profits [€]
Poland	2543	0,00	4864	1435	402701	37733	440434
Germany	1072	0,00	2.050	605	323.910	15.763	339.673
Switzerland	198	0,00	378	112	49.157	2.707	51.864
Belgium	197	0,00	377	111	43.392	2.695	46.087
Italy	71794	0,08	137.313	40.507	22.189.860	1.072.040	23.261.900
France	8523	0,01	16.300	4.809	1.548.533	127.044	1.675.577
Spain	28205	0,04	53.944	15.914	5.955.471	421.008	6.376.480
Portugal	11586	0,07	22.158	6.537	2.537.142	172.790	2.709.932
Austria	337	0,00	645	190	70.216	4.793	75.009
Greece	12108	0,07	23.158	6.832	2.510.316	180.595	2.690.911
UK	5123	0,01	9.798	2.890	1.528.483	76.266	1.604.749
Sweden	89	0,00	170	50	11.815	1.083	12.898
Total	141774	0,02	271.157	79.991	37.170.997	2.114.519	39.285.516

5.4 Discussion

In this part we will compare the results of the proposed methods with the ones demonstrated in older studies. First, let us focus on the quantity of coffee machines. As it was described in the previous chapter, Bush in “Preliminary Study on Hot Beverages Equipment” and EU in Ecodesign Working Plan 3 [11], [20] forecasts the quantity of professional espresso machines to be c.a. 1.5 mln in EU. It corresponds to the value of 1.4 mln of espresso machines estimated for the range of selected countries, which covers nearly 95% of EU population. However, the research presented in this thesis stretches beyond the previous analyses, determining the number of units of the most crucial market’s segments in terms of energy services. This categorization offers a more precise insight in the market structure and allows to focus on a preferable combination of traditional and automatic machines with a detailed subdivision for price size and number of spouts. The size of stock for the segments is the following:

a) 141,774 for professional machines (3 and 4 groups),
b) 180,294 for traditional machines (3 and 4) and automatic machines (above 12000€)
c) 517,091 for traditional machines (2,3 and 4 groups)
d) 616,959 for traditional machines (2,3 and 4 groups) and automatic machines (above 8000 €)

Due to the vast segmentation of restaurants as well as of particular kitchen appliances, it is challenging to compare the potential energy savings from coffee machine as analysed in this thesis with the conclusions of previous studies. Nevertheless, the confrontation of outcomes with some previous investigations into energy use in gastronomy service might be relevant. For instance, S. Mudie and M. Vadhati in "Low energy catering insights from a nove" [18], similarly to the author of the thesis, follow a bottom-up approach to investigate energy behavior of an "average" restaurant and forecast potential savings. The total yearly energy consumption of a kitchen use phase (excluding house operation – lightening, heating, entertainment etc.) is estimated to 335 187 kWh. The potential savings of 1912 kWh per espresso machine would be equal to 0,5% of total energy use of a kitchen. However, regarding only the electricity consumption, this ratio changes significantly. In " Electricity use in commercial kitchen" [43], S. Mudie et al. determine electricity use in kitchens to be c.a 53 268 kWh.

Consequently, the only way to decrease of electricity consumption by 3.5%. is improving coffee machine efficiency. On the other hand, the mentioned 1912 kWh of savings correspond to 25% of energy reduction a coffee machine itself. The saving of 25% is similar to the result of S. Mudie for the whole restaurant: it is consistent with the first energy saving strategy – 29 % of saving potential – and is relatively lower than the outcome of second strategy (46,24%). It is, however, worth to precise that the percentage estimation of savings might not be accurate due to the strong differentiation of energy consumption in restaurant market. One way to improve it would be to follow the approach of Energy Star [44], which, for the restaurant benchmark, recommends establishing the indicator of energy per floor area. Similarly, it would be meaningful to identify the demand for coffee machine per square meters of a gastronomy local.

It is also possible to study the obtained results from a wider perspective. For example, the electricity consumption in United Kingdom commercial catering sector is estimated to be around 2 TWh [45]. Consequently, a possible reduction from more efficient behaviour of espresso machine would result in savings between 0,5 to 5% of depending on the selected scenario. In the case of EU, where total electricity use for Hotel and Restaurant services is around 123 TWh [46], presented forecast allow for cutting of up to 1%.

Regarding CO_2 emissions reduction, one can remark that the total reduction value of 350 thousand tones would decrease a total emission in Hotels and restaurants sector by 0,32 %. Namely, it is equivalent to 863 million km driven by average car or 43 billion smartphones charging.

Chapter 6

Conclusion

The last chapter of thesis offers a more holistic approach for results analysis. The combine quantitative results are combined and discussed. The subchapter 5.3 presents the limitations of this research. At the end of the chapter conclusions are carries out.

6.1 Summary and Implications

This research aimed at confirming a feasibility of using professional coffee machines to provide two sorts of energy services: a) frequency containment reserve for the grid and b) improvement of the energy efficiency. Furthermore, the target of the thesis was to estimate the potential market for both the services. Based on the quantitative analysis of a) load profile of espresso machine La Marzocco operating at selected Café and b) stock quantity of coffee machines in major EU economies, as well as the qualitative analysis of the EU policy and energy labelling trends, it can be concluded that there is a potential for energy efficiency improvement in coffee machines, which are simultaneously capable of providing FCR services.

The quantitative results of this research regard three major elements:

a) Estimation of the stock quantity for 12 EU countries covering nearly 95 % of EU population
b) Analysis of potential energy savings of espresso machine
c) Forecast of disposable power for FCR services from given aggregation of coffee machines

In the case of step a) the outcomes of the thesis present the predicted quantity of appliances for selected countries in 4 different scenarios, depending on the type of a machine, number of spouts and price tag. The analysis was based on two main data sources: the national statistic offices and sales information from gastronomy association.

The next step b) was to investigate the potential savings from the energy efficiency increase. Two approaches have been suggested: the first focuses on the elimination of the idle mode during night-time whereas the second examines the theoretical opportunity of decreasing thermal flux between coffee boiler and environment.

The last quantitative part estimates that the disposable power for providing FCR services is depending on a given aggregation of coffee machines for five selected time intervals: the idle state during the night (the worst case scenario, when no coffees are made), the morning time between 8:00 AM and 10:00AM, the midday time 10:00 AM- 6:00 PM, the evening time 6:00PM – 8 :00PM and closing time 8:00 PM to 9:00 PM. In order to achieve these results, the algorithm innovatively adapts Croston's intermittent demand methods. Firstly, it forecasts demand arrivals and demand sizes of coffee production. Then, it generates respective power loads for given time intervals.

The quantitative parts are then combined to present estimations of market size, potential energy savings, CO_2 reduction scale and profits obtainable for the four scenarios (based on stock estimation) and 2 variants (when a machine is switched off during night and when it is not). Consequently, one may conclude that in terms of financial benefits the increase of energy efficiency is much more advantageous than in the case of FCR services. Still, both services can be provided simultaneously.

In addition, there numerical analysis is complemented with a qualitative study on energy labelling trends in the EU. The role and potential of these upcoming trends have been investigated, whereas a particular emphasis has been put on the discussion about the inclusion of professional coffee machines. Five major eco-labels, which already take coffee machines into consideration, are described. Furthermore, the most relevant standard for measuring energy efficiency has been characterized.

Collectively, our results appear consistent with KOENA tec's primary assumption. They prove that it is feasible to increase the energy efficiency of a coffee machine and, simultaneously, to participate in delivering FCR services. The outcomes provide a strong support for the launch of the KOENA tec's program with Swiss TSO (BKW) and are relevant to its future business strategy. Furthermore, the conclusions of the thesis can serve as an indicator for the inclusion other gastronomy appliances to start-up projects regarding energy efficiency and balancing grid services.

As it has been discussed, the combination of both previously mentioned energy services may be considered a promising step towards a more sustainable energy economy and contribute to EU green policy. The feasibility of this joined solution has a potential not only to decrease carbon footprint but also to improve grid security concurrently.

This thesis contributes to a growing corpus of research aimed at demonstrating the opportunity of providing grid balancing services as an addition to energy efficiency improvement for espresso machines. It is an accurate analysis of how the wider problem of grid security and sustainability can be faced with local gastronomy points and small-scale appliances. Furthermore, the conclusion of the thesis evaluates the approach to the FCR market, proving that solutions for complementary problems to energy transition can be proposed basing on available measures. What is more, the quantitative outcomes might serve as a potential comparison reference for future research.

6.2 Limitations and Future Work Opportunities

Our research about opportunities for combination of energy efficiency and providing FCR services for coffee machines was based on a defined methodology and data collected from a particular espresso machine. Furthermore, this investigation is set up in a very particular context of energy market, which strongly differs from country to country, as well as specific technical and food industry requirements. It naturally results in various limitations of the study. It will be relevant to briefly describe main concerns regarding the methodology, data and overall approach.

The basis for the estimation of the market potential was to forecast a possible stock quantity of coffee machines within major EU economies. One concern about these findings was the assignation of single coffee machine to every gastronomy point. Although the author tried to minimalize the error by predefining the gastronomy points according to selection of national NACE statistics, the outcome might still be uncertain, especially that due to scarcity of other data it is futile to conduct plausibility check. Similarly, the lack of other reliable studies does not allow to verify the second step for the methodology – namely, to identify the number of targeted appliances, based on their energy and power consumption.

This step might also suffer from the assumption that distribution of the stock is exact, as well as the distribution of sales.

Secondly, the methodology to estimate the energy efficiency increase for a coffee boiler serves only as scientific analysis of a theoretical upper bond value rather than a direct recommendation for the coffee industry. Although the author of the thesis believes that an investigation of theoretical improvement border is relevant, it might not result in direct beneficial incentives.

Furthermore, there are some limitations to the estimation of FCR services. First, it is assumed that the bottleneck of such a service will be delivering power to the grid, i.e. power reduction of a coffee machine rather than receiving power from the grid. This, however, should be verified and discussed. Secondly, the impact of delivering the balancing services on the thermodynamic state of steam and water and, consequently, on the product quality, should be analysed. What is more, the whole issue of connecting coffee machines in clusters and then to the grid needs to be taken into consideration. Apart from that, one may decide to consider different approaches for the applied methodology. It can be rewarding to examine other forecasting techniques, like for example the application of deep neural networks such as Long Short-Term Memory networks (LSTM). Such a focus on machine learning might, perhaps, not only improve the results, but it might also be advantageous for real-time analysis. Application of LSTM was considered in this thesis, however, after a consultation with colleagues from KOENA tec, the idea was rejected due to its uncertainty of obtaining reasonable outcomes and a significant extension of the workload.

Another major source of limitations for the presented results is the lack of multiple data sources. The whole data analysis process was based on the power consumption from a single coffee machine located in a particular café in Stuttgart. It is then possible that the results are biased due to a specific power behaviour of a given coffee machine. Moreover, a single data source undermines the process of projecting the results on all the gastronomy points in EU, independent on geography, restaurant size, nationality and culture.

Finally, one should take into consideration the energy market constraints. It was assumed that FCR services are provided or will be provided within all preselected countries. Although there is a trend of balancing market liberalization, it is necessary to point out that nowadays the approach to balancing grid varies among nations. For instance, in Portugal providing FCR services is mandatory and non-remunerated [47]. However, the complex analysis of the national energy markets exceeds the scope of the thesis and has not been widely investigated.

Certainly, the future investigations would be crucial to validate conclusions that can be drawn from this thesis. Eventual forthcoming studies could further develop and confirm these initial findings by increasing the scope of available dataset to a larger and more dispersed set of coffee machines and gastronomy points. In addition, the investigation of delivering FCR in the direction from the grid and its impact on product quality should be conducted. Although the presented analysis is based on real data from an actually working machine, it would be relevant to prove the feasibility of providing FCR in a real-life environment.

Annex 1

Quantitative Results

This annex includes the outcomes of the thesis for the three scenarios (2,3 and 4) with both variants (a,b) not presented in the main part of the work.

Table 7.1 The detailed quantitative results for scenario 2, variant a.

Traditional professional espresso machines (group 3 and 4) and automatic machines (price above 12000 €)							
Country	**Number of espresso machines**	**Percentage of the FCR market**	**Energy savings [GWh]**	**CO2 reduction [t]**	**Savings due to energy efficiency [€]**	**Savings due to providing FCR services [€]**	**Total profits [€]**
Poland	4.665	0,01	1.243	367	102.909	114.138	217.047
Germany	8.824	0,01	2.351	694	371.463	216.314	587.777
Switzerland	1.237	0,01	330	97	42.855	29.938	72.792
Belgium	847	0,01	226	67	25.985	20.340	46.325
Italy	73.111	0,07	19.480	5.747	3.148.034	1.795.687	4.943.721
France	14.270	0,01	3.802	1.122	361.209	350.116	711.325
Spain	30.584	0,04	8.149	2.404	899.675	750.923	1.650.599
Portugal	12.462	0,07	3.320	980	380.185	305.692	685.878
Austria	1.130	0,01	301	89	32.758	27.304	60.062
Greece	13.024	0,07	3.470	1.024	376.166	319.501	695.667
UK	19.361	0,02	5.159	1.522	804.755	475.187	1.279.943
Sweden	1.411	0,01	376	111	26.095	34.212	60.307
Total	180.924	0,03	48.207	14.221	6.572.090	4.439.352	11.011.441

Table 7.2 The detailed quantitative results for scenario 2, variant b.

Traditional professional espresso with 3 or 4 groups and automatic machines (price above 12000 €) - coffee machines switched off during nights							
Country	**Number of espresso machines**	**Percentage of the FCR market**	**Energy savings [GWh]**	**CO2 reduction [t]**	**Savings due to energy efficiency [€]**	**Savings due to providing FCR services [€]**	**Total profits [€]**
Poland	4.665	0,01	8.921	2.632	738.689	69.421	808.110
Germany	8.824	0,01	16.876	4.978	2.666.393	131.538	2.797.931
Switzerland	1.237	0,01	2.366	698	307.616	18.232	325.848
Belgium	847	0,01	1.619	478	186.521	12.397	198.919
Italy	73.111	0,08	139.832	41.250	22.596.843	1.091.707	23.688.551
France	14.270	0,01	27.293	8.051	2.592.789	212.882	2.805.672
Spain	30.584	0,04	58.496	17.256	6.457.943	456.550	6.914.493
Portugal	12.462	0,08	23.834	7.031	2.729.003	185.875	2.914.878
Austria	1.130	0,01	2.161	638	235.142	16.631	251.773
Greece	13.024	0,08	24.909	7.348	2.700.148	194.270	2.894.418
UK	19.361	0,02	37.029	10.924	5.776.600	288.919	6.065.518
Sweden	1.411	0,01	2.699	796	187.312	20.831	208.143
Total	180.924	0,03	346.036	102.081	47.174.999	2.699.254	49.874.254

Table 7.3The detailed quantitative results for scenario 3, variant a.

Traditional professional espresso machines (group 2,3 and 4)							
Country	**Number of espresso machines**	**Percentage of the FCR market**	**Energy savings [GWh]**	**CO2 reduction [t]**	**Savings due to energy efficiency [€]**	**Savings due to providing FCR services [€]**	**Total profits [€]**
Poland	14.662	0,02	3.907	1.153	323.484	359.761	683.246
Germany	6.631	0,00	1.767	521	279.158	162.448	441.606
Switzerland	1.145	0,01	305	90	39.645	27.661	67.306
Belgium	1.617	0,01	431	127	49.624	39.260	88.884
Italy	182.628	0,18	48.661	14.355	7.863.641	4.486.228	12.349.869
France	28.679	0,02	7.641	2.254	725.941	704.108	1.430.049
Spain	158.927	0,20	42.346	12.492	4.675.023	3.903.975	8.578.998
Portugal	47.454	0,27	12.644	3.730	1.447.737	1.165.352	2.613.089
Austria	3.366	0,02	897	265	97.592	82.247	179.840
Greece	49.573	0,27	13.209	3.897	1.431.837	1.217.432	2.649.269
UK	20.616	0,02	5.493	1.620	856.922	506.020	1.362.941
Sweden	1.793	0,01	478	141	33.161	43.599	76.760
Total	517.091	0,09	137.779	40.645	17.823.765	12.698.092	30.521.857

Table 7.4 The detailed quantitative results for scenario 3, variant b.

Traditional professional espresso with 2,3 or 4 groups - coffee machines switched off during nights							
Country	**Number of espresso machines**	**Percentage of the FCR market**	**Energy savings [GWh]**	**CO2 reduction [t]**	**Savings due to energy efficiency [€]**	**Savings due to providing FCR services [€]**	**Total profits [€]**
Poland	14.662	0,03	28.043	8.273	2.321.998	218.746	2.540.744
Germany	6.631	0,01	12.682	3.741	2.003.819	98.791	2.102.610
Switzerland	1.145	0,01	2.189	646	284.573	16.848	301.421
Belgium	1.617	0,02	3.092	912	356.204	23.900	380.103
Italy	182.628	0,20	349.294	103.042	56.445.861	2.727.403	59.173.263
France	28.679	0,03	54.851	16.181	5.210.867	428.089	5.638.956
Spain	158.927	0,22	303.965	89.670	33.557.698	2.373.426	35.931.124
Portugal	47.454	0,30	90.760	26.774	10.391.974	708.499	11.100.473
Austria	3.366	0,02	6.439	1.899	700.527	50.034	750.560
Greece	49.573	0,30	94.814	27.970	10.277.847	740.161	11.018.008
UK	20.616	0,02	39.430	11.632	6.151.054	307.663	6.458.717
Sweden	1.793	0,01	3.430	1.012	238.030	26.537	264.568
Total	517.091	0,10	988.989	291.752	127.940.451	7.720.097	135.660.548

Table 7.5 The detailed quantitative results for scenario 4, variant a.

Traditional professional espresso machines (group 2,3 and 4) and automatic machines (price above 8000 €)							
Country	**Number of espresso machines**	**Percentage of the FCR market**	**Energy savings [GWh]**	**CO2 reduction [t]**	**Savings due to energy efficiency [€]**	**Savings due to providing FCR services [€]**	**Total profits [€]**
Poland	19.090	0,03	5.086	1.500	421.155	468.523	889.678
Germany	23.550	0,02	6.275	1.851	991.440	578.109	1.569.549
Switzerland	3.860	0,02	1.028	303	133.701	94.370	228.071
Belgium	6.418	0,06	1.710	504	197.006	157.221	354.227
Italy	186.578	0,18	49.714	14.666	8.033.735	4.583.277	12.617.012
France	41.655	0,03	11.099	3.274	1.054.408	1.022.902	2.077.310
Spain	169.708	0,21	45.219	13.340	4.992.141	4.168.822	9.160.963
Portugal	50.749	0,29	13.522	3.989	1.548.269	1.246.306	2.794.575
Austria	5.629	0,03	1.500	442	163.185	137.834	301.019
Greece	53.017	0,29	14.126	4.167	1.531.306	1.302.038	2.833.344
UK	50.839	0,04	13.546	3.996	2.113.185	1.248.525	3.361.710
Sweden	5.866	0,03	1.563	461	108.475	143.659	252.134
Total	616.959	0,10	164.389	48.495	21.288.006	15.151.586	36.439.592

Table 7.6 The detailed quantitative results for scenario 4, variant b.

Traditional professional espresso with 2,3 or 4 groups and automatic machines (price above 8000 €) - coffee machines switched off during nights							
Country	**Number of espresso machines**	**Percentage of the FCR market**	**Energy savings [GWh]**	**CO2 reduction [t]**	**Savings due to energy efficiency [€]**	**Savings due to providing FCR services [€]**	**Total profits [€]**
Poland	19.090	0,03	36.511	10.771	3.023.085	284.867	3.307.953
Germany	23.550	0,02	45.042	13.287	7.116.641	351.489	7.468.129
Switzerland	3.860	0,03	7.382	2.178	959.715	57.403	1.017.119
Belgium	6.418	0,07	12.275	3.621	1.414.129	95.613	1.509.742
Italy	186.578	0,20	356.849	105.270	57.666.812	2.786.403	60.453.215
France	41.655	0,04	79.670	23.503	7.568.624	621.898	8.190.522
Spain	169.708	0,24	324.583	95.752	35.833.997	2.534.438	38.368.435
Portugal	50.749	0,32	97.062	28.633	11.113.599	757.715	11.871.314
Austria	5.629	0,04	10.766	3.176	1.171.355	83.827	1.255.182
Greece	53.017	0,32	101.401	29.913	10.991.842	791.596	11.783.438
UK	50.839	0,05	97.235	28.684	15.168.618	759.064	15.927.682
Sweden	5.866	0,04	11.220	3.310	778.641	87.368	866.010
Total	616.959	0,12	1.179.996	348.099	152.807.057	9.211.682	162.018.739

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