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Hybrid Storage System for peak shifting applications

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Contents

1 Introduction

Climate change is one of the biggest obstacles currently affecting the international community. Following United Nations in the Sustainable Development Goals campaign, it is paramount to take action on this influential matter. Moreover substantial funds have been allocated to research projects that are trying to address this unavoidable problem. An efficient approach in dealing with the climate change is the reduction of CO_2 emission. The data United Nations data show that an annual reduction in CO_2 emission of 7.6% is necessary to limit the rise in global temperature to 1.5°C [Nations, 2020]. One major contributor to the CO_2 discharge globally is the built environment sector, that is human-made environment such as homes or buildings, that provides setting for human activity. Buildings and constructions account for as much as 36% of global final energy use and 39% of energy-related CO_2 emissions when upstream power generation is included [Programme, 2017].

There are numerous strategies that can be used to make progress towards lowering the carbon footprint. Literature nowadays focuses mostly on the minimization of CO_2-intensive energy intake or the reduction of its running cost instead of concentrating on increasing the production of green electricity (i.e. electricity produced in an environmentally friendly way). This project focuses explicitly on adapting the consumption of energy that is used by homes powered by electricity. As the amount of CO_2 emitted by the energy producers supplying the Electrical Grid varies throughout the day, we are able to reduce the CO_2 emissions of the built environment sector by shifting electrical demand to low CO_2 emission intervals. The emitted amount of CO_2 per produced kWh is called the CO_2 intensity. An exemplary data during the day is shown in Figure 1.

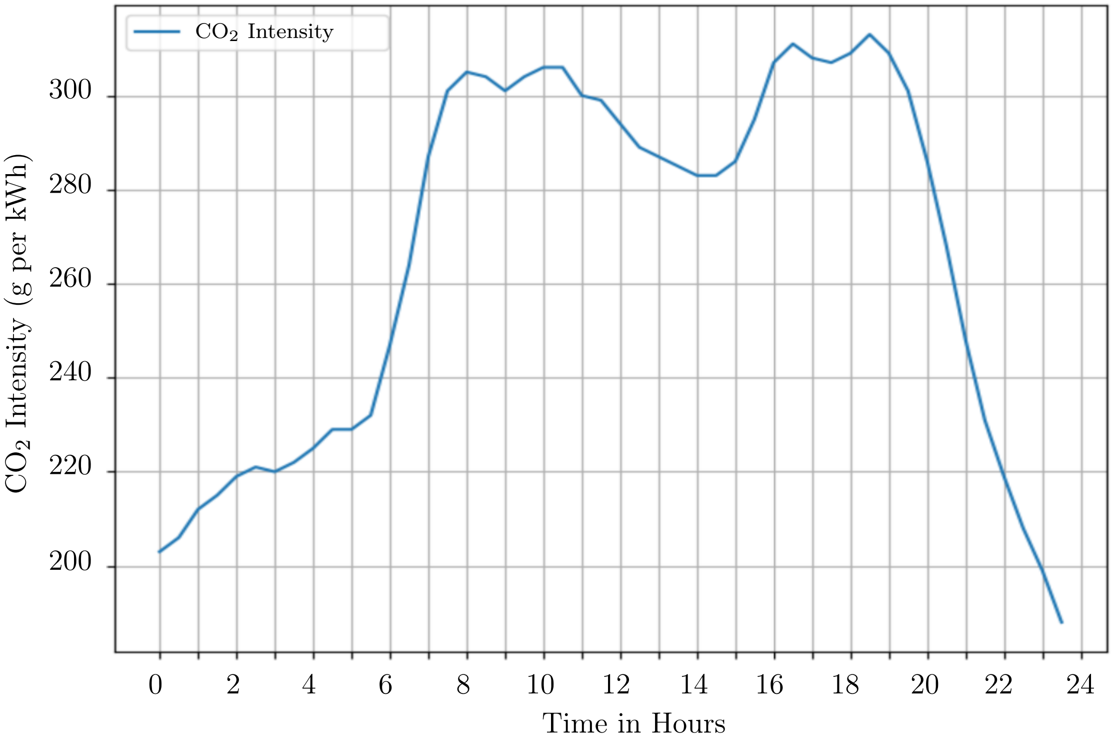

Figure 1: Exemplary data of the CO_2 Grid intensity level over a day.

It is noticeable that the CO_2 grid output early in the morning and late in the evening is usually considerably lower than during the day. Houses nowadays use the Electric Grid as power source whenever the domestic appliances are in need for electricity. The scope of this project is to introduce different kinds of energy storage to allow a more efficient distribution of the power intake.

The reduction of the CO_2-intensive Grid electricity intake motivates us to introduce the innovative hybrid storage system RED WoLF (Rethink Electricity Distribution Without Load Following). The ultimate goal is to only use Grid resources, when the CO_2-intensity is low and self supply when the CO_2-intensity is high and thus decrease the overall CO_2-emissions. The components and their interactions are illustrated in Figure 2 and explained in the following.

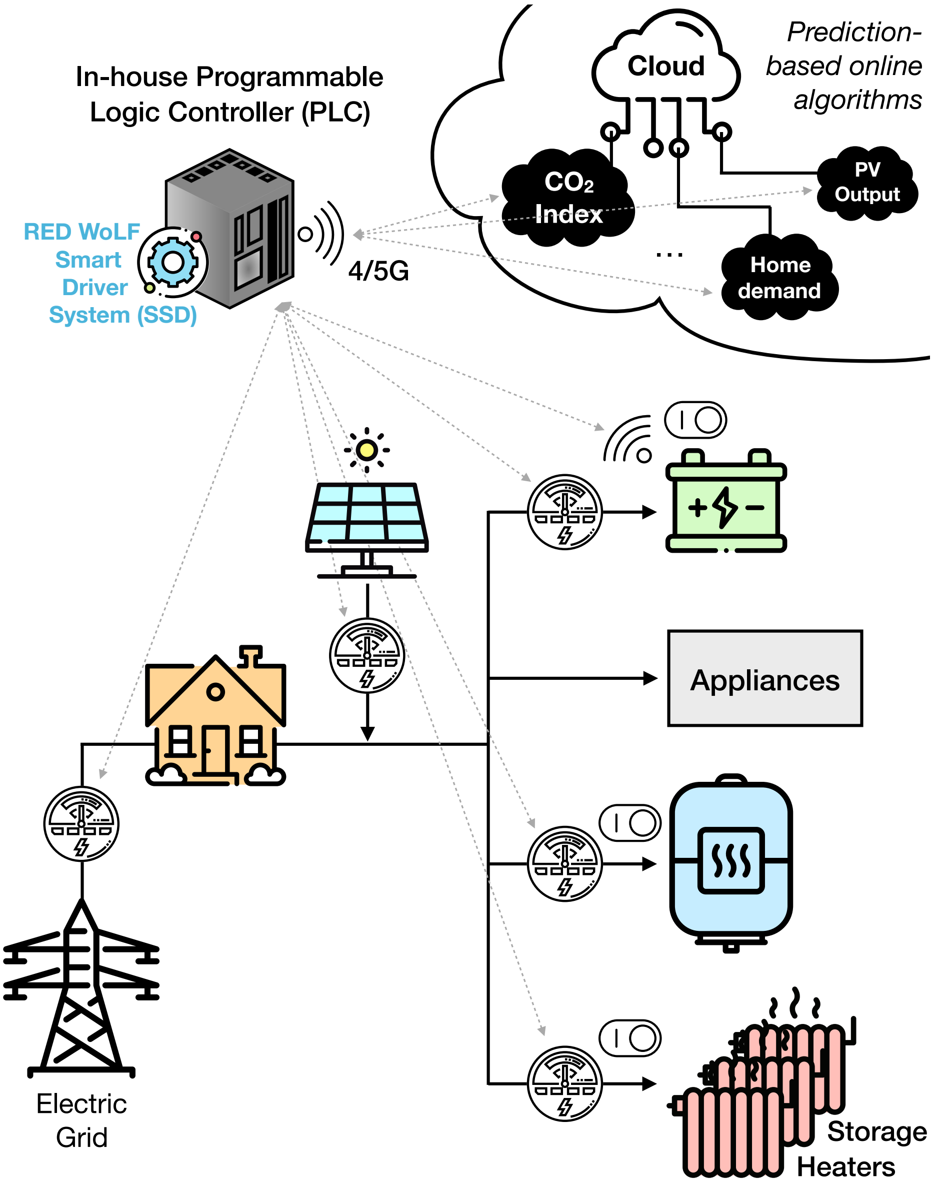

Figure 2: System components and setup for the RED WoLF System [Interreg, 2009].

In order to reduce the dependencies from the Electric Grid, the system must be able to satisfy the demand for heating, hot water and electric energy for household appliances. Therefore the RED WoLF components consist of storage heaters (SHs) for space heating, a hot water cylinder for hot water storage and a battery for electricity supply. For efficiency reasons, a PV array is also included as a component in the RED WoLF system. The power distribution is coordinated by the In-house Programmable Logic Controller (PLC), which uses predictions for the PV output and the home demand for heat, hot water and electricity. Further predictions are made for the CO_2-intensity, updated and adjusted to the real data every hour. In this way, the electrical demand that cannot be covered by the PV array itself is adjusted to the time interval when the CO_2-intensity of the Grid is the lowest (except for the appliances which are powered on demand). In the case of energy excess, the PV array will also supply the Grid after fully loading the system components.

After determining the estimated energy demand and production, the RED WoLF system handles the energy distribution of the dwelling. The schematic energy flow is shown in Figure 3.

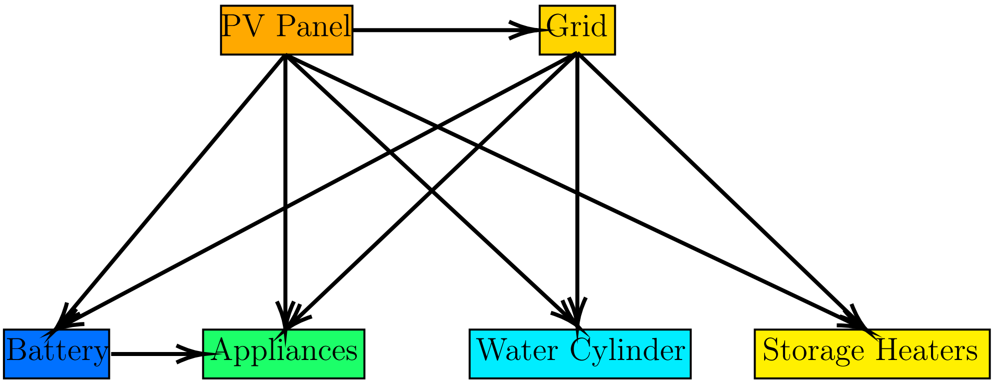

Figure 3: Schematic representation of the energy flow in a dwelling using the RED WoLF System (based on representation presented in: [Shukhobodskiy and Colantuono, 2020])

The PV Panel and the Electric Grid provide the energy, which is distributed on the Storage Heaters, the Hot Water Cylinder, the Appliances and the Battery. Depending on the house configuration, there are different possibilities to set the priorities in order to maximise efficiency. Whereas the Appliances will always need to be supplied first, the priorities for the storage components depend on the maximum rate of electric energy intake (which is country dependent). If the power supply from the PV Panel is sufficient or the CO_2-intensity form the Grid is low, the Battery is charged for the purpose of supplying the Appliances during the high CO_2-intensities.

One specific area where this strategy may be beneficial is the North West Europe (NWE), particularly the British Isles and Northern France. Due to its close proximity to the Atlantic ocean, these areas have relatively mild winters. Additionally, on these locations, there is an increased penetration of renewable energy projected, particularly wind based energy. The energy regulation and energy landscape in the NWE is also another factor that should be considered. In the United Kingdom (UK) the domestic sector was responsible for the consumption of 41.3 millions tons of oil equivalent worth of energy in 2019, which sums up to about 27% of the national consumption [Department for Business, 2019]. In Northern Ireland during 2010 around 68% (and up to 82% in rural areas) of households used oil to heat their houses, a method which produces a lot of Greenhouse gas [Council, 2011]. Currently around 75% of the France's national energy consumption is generated by nuclear power. However an increasing amount of these nuclear power plants are ageing and are not set to be replaced. The French government has instead opted to increase the usage of renewable energy [Shukhobodskiy and Colantuono, 2020].

In the UK, energy policy revolves around the *energy trilemma*, that is: energy should be cheap, secure, and clean. Fulfilling all three aspects at the same time is not an easy task to accomplish. However, making the greatest possible use of green energy and avoiding the use of fossil fuels is an important step towards achieving the EU's climate targets. This is why the decarbonisation of the electricity system is also the in immediate goal of the UK [of Engineering, 2015].

In this research project, which is carried out by students as a part of the First Virtual ECMI Modelling Week 2020, we want to reproduce the results of the RED WoLF project, which is an European program with the goal of reducing CO_2 emissions of the housing sector. The original work is found in "RED WoLF: Combining a battery and thermal energy reservoirs as a hybrid storage system" [Shukhobodskiy and Colantuono, 2020]. Our addition was constructing a working seven day model, which generalizes the base project (more about this later).

This concludes the introduction for this student research project. Having clarified the conditions and the scope of the project, chapter 2 will focus on more detailed analyses regarding assumptions, functionality and application of the method to different scenarios. In chapter 3 the results of the research are discussed. In chapter 4 a personal statement by the authors of this project is made regarding the dynamics of the group work and the distribution of the tasks. This report ends with an assessment for the students by the instructor Dr. Alexander Shukhobodskiy in chapter 5.

2 Report content

The content of this report is organised in four different subsections: First, the basic RED WoLF algorithm is explained in subsection 2.1, which summarises the fundamentals for this project found in [Shukhobodskiy and Colantuono, 2020]. In subsection 2.2 two measures are proposed to advance the basic algorithm and create a stable system for multiple days. We further adapt the advanced algorithm for different environments in subsection 2.3. These results are finally being used to simulate various scenarios with existing data in subsection 2.4.

2.1 The basic RED WoLF Algorithm

In this subsection we will carefully explain how does the base RED WoLF algorithm function. We ought to explain the decision making, and showcase the procedure. Firstly, a list of all variables that our system uses is provided in Table 1.

Table 1: Predefined parameters and variables

B_{IMax}	Maximum rate of battery intake in kW
B_{Max}	Maximum battery capacity in kWh
C_{IMax}	Maximum rate of Cylinder intake in kW
H_{IMax}	Maximum rate of house intake from Grid in kW
$\widetilde{H}_{\text{IMax}}$	Maximum rate of heat intake in kW
B_D	Battery demand in kW
B_{level}	Battery level in kWh
C_D	Cylinder demand in kW
C_{level}	Cylinder level in kWh
C_{Setup}	The energy requited by user obtained in 24h in kWh
$\widetilde{H}_D$	Heat demand in kW
$\widetilde{H}_{\text{level}}$	Heat level in kWh
$\widetilde{H}_{\text{Setup}}$	The energy needed for SHs to obtain in 24 h in kWh
P_{P2A}	Predicted power to appliance in kW
P_{PV}	Predicted power from PV in kW
T_{PV}	Actual power from PV in kW
T_{P2B}	Actual power to battery in kW
T_{PFB}	Actual power from battery in kW
T_{P2H}	Actual power for heating in kW
T_{P2C}	Actual power to Cylinder in kW
T_{PFG}	Actual power from Grid in kW
T_{P2G}	Actual power to Grid in kW
T_{P2A}	Actual power to Appliances in kW
Q	CO_2 intensity level prediction in gCO_2/kWh
δ	CO_2 intensity threshold in gCO_2/kWh

Notice that some of the parameters are predefined locally, and are depending on the house equipment (H_{IMax}, $\widetilde{H}_{\text{IMax}}$, B_{IMax}, C_{IMax} and B_{Max}). Others, for example H_{Setup} and C_{Setup}, are adjustable by the dwellers or automatically set up for a fixed period of time. Necessary inputs for a legitimate simulation are the 24h PV generation forecast (P_{PV}), household consumption forecast (P_{P2A}) and the 24h CO_2 intensity from the Grid forecast (Q). The base system will operate in the time span of 24h, which we will later optimize to work for multiple days.

Heat, battery and cylinder demand are defined in the following way:

$$\widetilde{H}_D = \widetilde{H}_{\text{Imax}} \cdot Heavy(\widetilde{H}_{\text{Setup}} - \widetilde{H}_{\text{level}}), \tag{1}$$
$$B_D = B_{\text{Imax}} \cdot Heavy(B_{\text{Setup}} - B_{\text{level}}) \tag{2}$$
$$C_D = C_{\text{Imax}} \cdot Heavy(C_{\text{Setup}} - C_{\text{level}}) \tag{3}$$

where $Heavy(x) = \begin{cases} 1 & \text{if } x > 0, \\ 0 & \text{if } x \leq 0. \end{cases}$

This means that unless the storage fulfills the daily required energy, the demand for the storage is the maximum rate of heat intake, otherwise it is zero. Next, we will make an introduction to the integral balance of the system:

$$\mathbb{I} = \int_{\hat{t}}^{\mathbb{T}} (P_{P2A}(t) - P_{PV}(t))/60dt + C_{\text{Setup}} - C_{\text{Level}} + \widetilde{H}_{\text{Setup}} - \widetilde{H}_{\text{Level}}. \tag{4}$$

Variable t represents time, $\hat{t}$ is the current time and $\mathbb{T}$ is the time up to which the prediction is made (in minutes). This integral defines the difference between the total energy demand and the energy generated by the PV array. In the case when $\mathbb{I} \leq 0$, the amount of generated energy is larger than what is needed for consumption. However if $\mathbb{I} > 0$, the predicted generated energy is lower than the required energy. Consequently, we can modify the time we supply the house with the Grid energy based on forecasts. In other words, when PV generation forecast is high, the Grid is used a lot less. The rate of power intake is defined as:

$$\omega = \int_{1}^{\mathbb{T}} P_{P2A}(t)dt/\mathbb{T} + \widetilde{H}_{\text{IMax}} + C_{\text{IMax}} + B_{\text{Level}}. \tag{5}$$

The power intake is therefore the sum of the storage demands and the average appliances intake.

Time for which we are allowed to intake power is the following:

$$\mathbb{T}_{int} = \left[max \left(\frac{60 \cdot \mathbb{I}}{\omega}, \frac{C_{\text{Setup}} - C_{\text{Level}}(1)}{C_{\text{IMax}}}, \frac{H_{\text{Setup}} - H_{\text{Level}}(1)}{H_{\text{IMax}}} \right) \right] \tag{6}$$

Rearranging Q array grants us a monotonically increasing array Q_{sort}. By doing so, it is possible to define the CO_2 threshold, above which we are not allowed to take energy from the Grid to charge the components:

$$\delta = Q_{sort}(\mathbb{T}_{\text{int}}) \text{ for } \mathbb{I} > 0, \text{ or } \delta = 0 \text{ for } \mathbb{I} \leq 0. \tag{7}$$

In other words, if $\delta \leq Q(t)$, we won't supply from the Grid. In that case, if $T_{P2A} \geq T_{PV}$ (the power from PV does not cover the demand), power is drawn from the battery to supply the appliances. However if the battery is insufficient, we rely on the Grid. Thus:

$$T_{PFG} = (T_{P2A} - T_{PV}) \cdot Heavy(T_{P2A}/60 - T_{PV}/60 - B_{\text{level}}), \tag{8}$$

$$T_{PFB} = (T_{P2A} - T_{PV}) \cdot Heavy(T_{P2A}/60 - T_{PV}/60 - B_{\text{level}}). \tag{9}$$

On the other hand, if $T_{P2A} \leq T_{PV}$, there is excess PV power: $E = T_{PV} - T_{P2A}$. This excess can be spent on different ways, based on its quantity.

Case 1. $E < C_D$.

In this case we transfer all of the surplus power to the water cylinder. Thus:

$$T_{P2C} = E \cdot Heavy(C_{\text{Setup}} - C_{\text{level}}). \tag{10}$$

Case 2. $E \geq C_D \land E < C_D + \widetilde{H}_D$.

Here,

$$T_{P2C} = C_D, \tag{11}$$

$$T_{P2H} = (E - C_D) \cdot Heavy(\widetilde{H}_{\text{Setup}} - \widetilde{H}_{\text{level}}). \tag{12}$$

This would mean that the water cylinder is our priority, since we supply it first.

Case 3. $E \geq C_D + \widetilde{H}_D \wedge E < C_D + \widetilde{H}_D + B_D$.

Therefore our algorithm is as follows:

$$T_{P2C} = C_D, \tag{13}$$

$$T_{P2H} = \widetilde{H}_D, \tag{14}$$

$$T_{P2B} = min((E - C_D - \widetilde{H}_D), B_{\text{IMax}}) \cdot Heavy(B_{\text{Max}} - B_{\text{level}}). \tag{15}$$

This is done with the intention to charge the battery as much as possible.

Case 4. $E \geq C_D + \widetilde{H}_D + B_D$

Finally:

$$T_{P2C} = C_D, \tag{16}$$

$$T_{P2H} = \widetilde{H}_D, \tag{17}$$

$$T_{P2B} = B_D, \tag{18}$$

$$T_{P2G} = E - (C_D + B_D + \widetilde{H}_D). \tag{19}$$

Here we export the excess power to the Grid, as we have sufficient energy. Now, lets assume that $Q < \delta$. The maximum power that can be directed into the house is

$$M_{HPV} = H_{\text{IMax}} + T_{PV}. \tag{20}$$

As the CO_2 level is bellow the threshold, we are allowed to use the Grid energy. Our equations now become:

$$T_{P2C} = \min(C_D, (M_{HPV} - T_{P2A}) \cdot Heavy(C_{\text{Setup}} - C_{\text{level}})), \tag{21}$$

$$T_{P2H} = \min(\widetilde{H}_D, (M_{HPV} - T_{P2A} - T_{P2C}) \cdot Heavy(\widetilde{H}_{\text{Setup}} - \widetilde{H}_{\text{level}})), \tag{22}$$

$$T_{P2B} = \min(B_D, (M_{HPV} - T_{P2A} - T_{P2C} - T_{P2H}) \cdot Heavy(B_{\text{Max}} - B_{\text{level}})) \tag{23}$$

In the case of PV energy surplus, we are able to send all the excess of power into the Grid. We update the CO_2 intensity threshold only if the demand of SHs and the water cylinder is not satisfied as a result of it deviating from the starting predictions. This can be beneficial when the original predictions differ from the actual energy generation and consumption.

Below in Figure 4 is the plot of the CO_2 intensity along with the generated thresholds based on the power of the PV. Notice how the threshold is higher, the weaker the PV is. That means, if the PV has more power, the system will supply from the Grid less, and rely more on the photo-voltaic array.

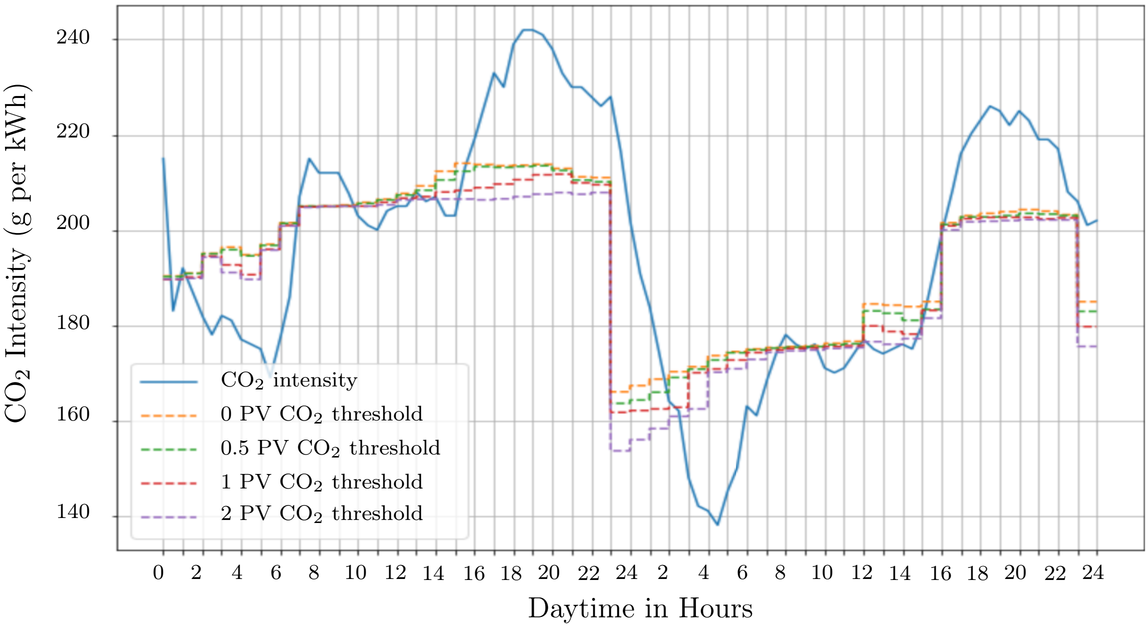

Figure 4: Different CO_2 thresholds based on the power of PV.

2.2 Generalised version of RED WoLF - the multiple day model

One major problem with the basic version of the RED WoLF algorithm is, that the introduction of a CO_2 threshold does not guarantee that space heating and hot water are always available. Since the CO_2 intensity is usually low in the morning and in the afternoon, the intervals, when the Grid is used, are set accordingly. With an especially low CO_2 intensity level in the afternoon, it can happen, that the storage are not loaded in the morning, despite the need of heat or hot water. Therefore it is not guaranteed that the energy levels of the SHs or the Hot Water Cylinder does not decrease to zero due to the consumption of heat or hot water. In the worst scenario, the CO_2 intensity minimum at the end of the day are always below those of the previous day and the new global minimum is selected for loading the storage. This could result in unheated houses for numerous days, until the CO_2 intensity level rises again.

We are proposing two approaches to correct this problem. The first one is advance the calculation method for the CO_2 threshold. There are always two days compared by the algorithm, so we use the energy consumption and generation predictions for at least the next 25 hours. The hours before 12 o'clock at night are considered the first day, the hours after the second day. This method consists of four steps, that are visualised in Figure 5:

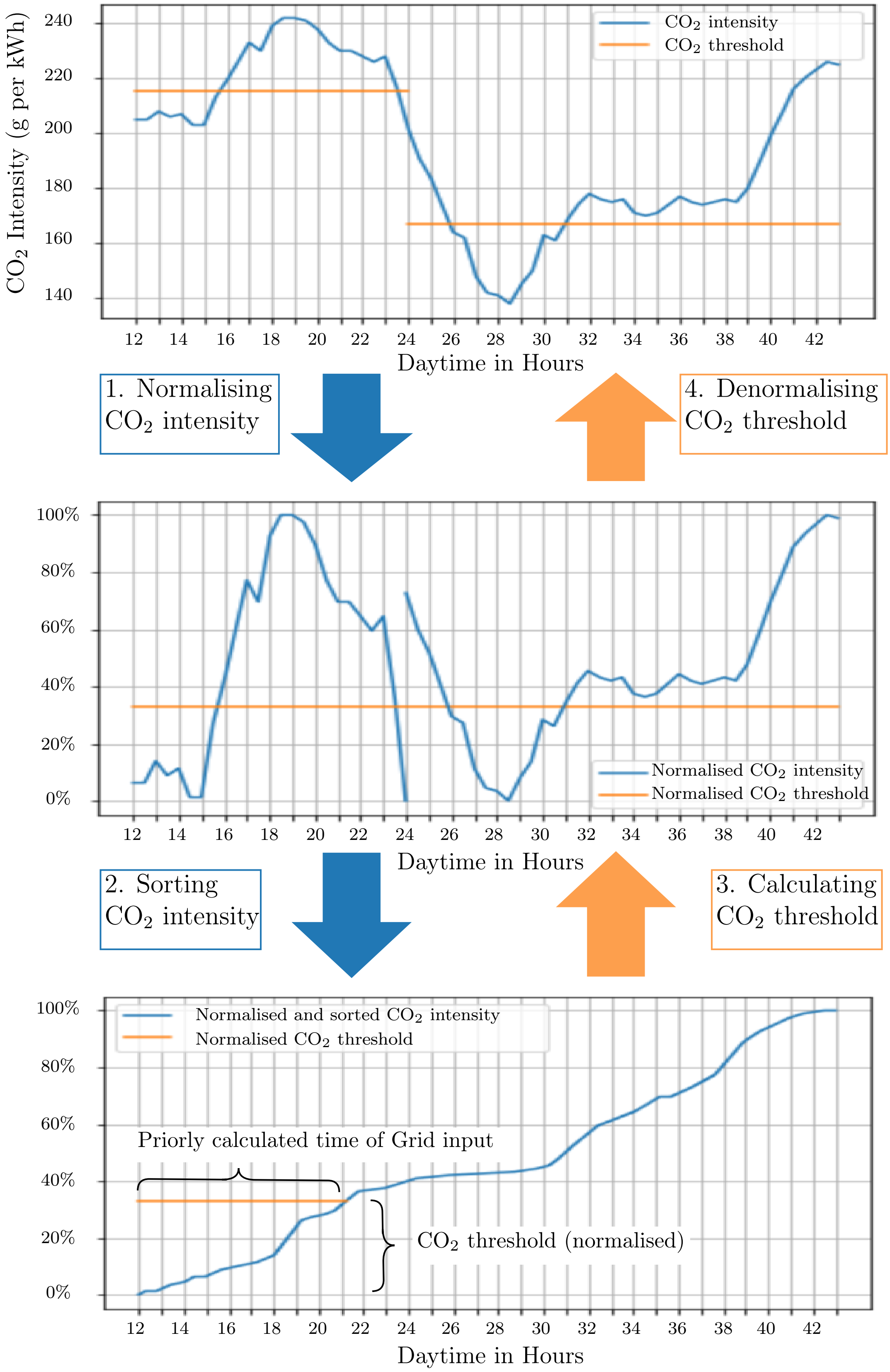

Figure 5: Process of calculating the CO$_2$ threshold by normalising two consecutive days and denormalising the CO$_2$ threshold.

1. **Normalising the CO_2 intensity:** By normalising the CO_2 intensity data for each day, local CO_2 intensity minimum, that occur on the current day, are as equally important as global minimum on the next day. This avoids long time intervals without energy intake from the Grid.
2. **Sorting the CO_2 intensity:** This step is the same as calculating the CO_2 threshold for the basic algorithm. The only difference is that the normalized CO_2 intensities are used instead of the real ones.
3. **Calculating the normalised CO_2 threshold:** The normalised CO_2 threshold is the value at the calculated time of Grid intake $\mathbb{T}_{int}$, as explained in the previous subsection. The calculation for $\mathbb{T}_{int}$ did not change.
4. **Denormalising the CO_2 threshold:** With the known maximum and minimum CO_2 intensity levels for each day, the normalised CO_2 threshold is being denormalised for the current and the next day, resulting in a different CO_2 thresholds for each day.

This normalisation technique creates scenarios that are much more stable compared to a calculation method with a single CO_2 threshold.

Nevertheless, while normalising the CO_2 intensity levels balances the usage of the Grid, it is still not guaranteed, that the heat or cylinder level falls to zero. Due to unforeseen circumstances, the energy consumption and generation will always differ from the predictions. So the second idea we introduce here is force loading. Heating and hot water should be always available, so if the energy level of the SH or the water cylinder decreases to zero, it will be force charged one hour until the CO_2 threshold is updated again, no matter the CO_2 intensity. This limits the efficiency of the system for the rare case of exceptional high energy demands, but at this point assuring energy supply is more important than saving CO_2.

There are different methods to stabilise the algorithm. Another approach worth testing might be executing the simulation for the next 24 hours and testing, if the storages are greater than zero. Is this not the case, than the simulation can be repeated with one hour less of prediction, until the storages only contain positive values. However, force load will always be required to overcome noise and unexpected demands.

2.3 Adapting the RED WoLF Algorithm for different environments

Unfortunately, our algorithm isn't as omnipotent as we would want it to be. Different countries have different housing infrastructures, thus our strategy may not be the most efficient one in some parts of the world. However, we are able to adapt the system, and make it work optimally in various regions. Namely, the maximum rate of house intake (H_{IMax}) deviates in European countries, hence the energy spending priorities must change. For example, in London we know that: $H_{\text{IMax}} = 25kW$, while in Belgium it is usually much lower: $H_{\text{IMax}} = 9kW$.

We propose that in Belgium the battery has to be charged first, whether we are above or bellow the threshold. When the CO$_2$ intensity is above the threshold and we have excess PV energy, we should examine whether that surplus is larger than the battery demand (instead of the cylinder demand, as we did before). After supplying the battery, the cylinder, SHs and the Grid are provided the power respectively.

In the case when the intensity is bellow the threshold, the algorithm is as follows:

$$T_{P2B} = \min(B_D, (M_{HPV} - T_{P2A}) \cdot Heavy(B_{\text{Max}} - B_{\text{level}})), \tag{24}$$

$$T_{P2C} = \min(C_D, (M_{HPV} - T_{P2A} - T_{P2B}) \cdot Heavy(C_{\text{Setup}} - C_{\text{level}})), \tag{25}$$

$$T_{P2H} = \min(\widetilde{H}_D, (M_{HPV} - T_{P2A} - T_{P2B} - T_{P2C}) \cdot Heavy(\widetilde{H}_{\text{Setup}} - \widetilde{H}_{\text{level}})) \tag{26}$$

The idea behind the changes is that the battery now charges the appliances most of the time, and it is used more often than in the previous version of the system. The savings are now higher when the PV panels are weak, as we are distributing energy efficiently with this improved algorithm (it would have been much lower with the old system). In Figure 6, we demonstrate how our algorithm functions for multiple days in the Belgium case. The storage levels, the CO$_2$ data and the power flow for the components are plotted.

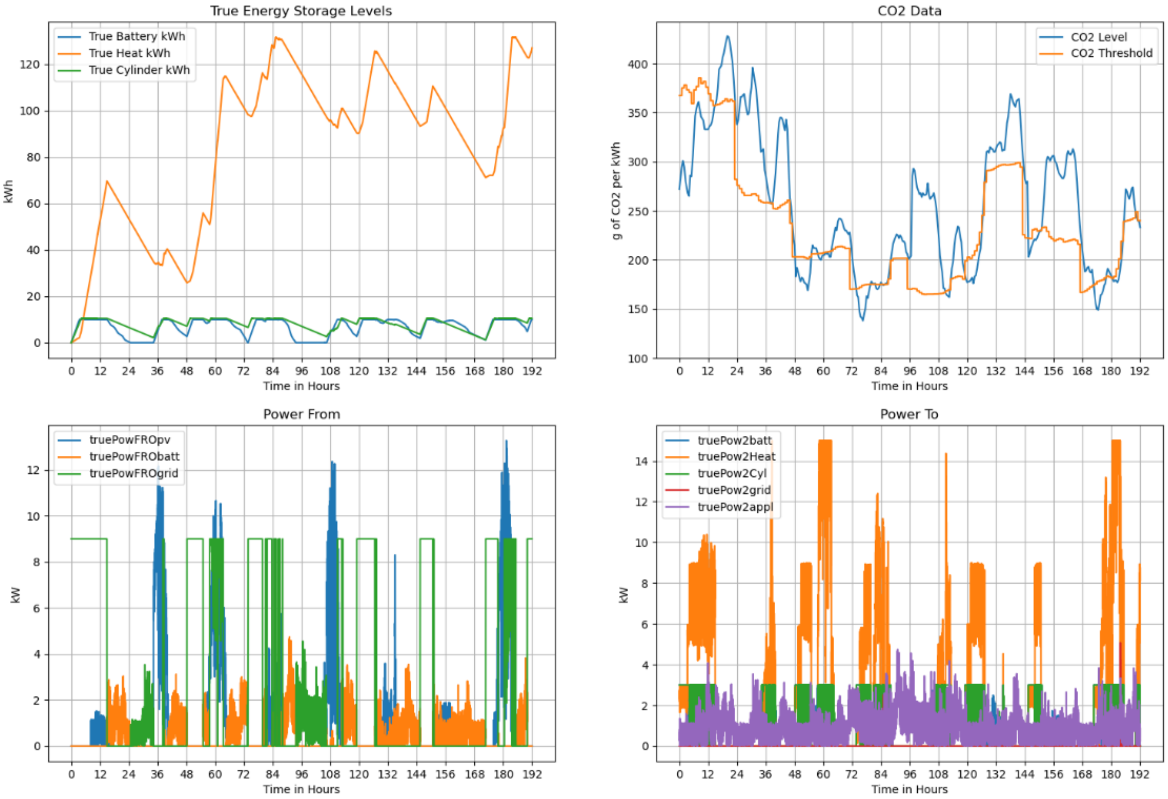

Figure 6: Power flow and CO$_2$ threshold for 8 days period

2.4 Application of the RED WoLF Algorithm using existing data as input

At this point we will apply the implemented RED WoLF algorithm for different countries and seasons. Additional scenarios with different PV array sizes will also be tested (half size, double size and no PV). To date, there is no detailed data for the daily consumption of hot water and space heating, so some assumptions are necessary for the distribution of the yearly demand, which is known. So we assume that most of the space heating (75%) is needed in winter, there is no space heating in summer and the remaining heating is equally distributed to spring and autumn. The yearly need for heat in kWh for certain countries is shown in table 2, according to [ovo energy, 2010] and [Agency, 2009], the max rate of house intakes are assumed values and depend on the specific tariff.

Table 2: Yearly energy demand per dwelling and maximum rate of house intake for specific countries.

country	yearly heat demand [kWh]	max rate of house intake [kW]
Spain	4291	5.5
Italy	9595	15
UK	12037	25
Poland	12084	25
France	12305	18
Germany	13572	34
Ireland	15816	25
Belgium	16630	9

The generalised algorithm is run for eight days of data in each season. The last day of the simulation uses the basic algorithm, because no further data is known for comparison. Each scenario starts with full storages and uses exemplary data for appliances demand and PV generation for the specific time of the year. We assume that the demand for heat and hot water is primarily distributed between 5 to 10 am and 5 to 10 pm with additional noise heavy demand over the whole day. As there is currently only eight days of CO_2 intensity level data available to us now, the same values are used for each scenario. Table 3 presents the relative savings of a dwelling in the UK for different PW array sizes in each season. There are some noticeable aspects about these numbers:

- Larger PV arrays result in higher CO_2 savings, as there is to expect.
- Even with no PV array, the system saves more than 20% of CO_2 emissions by solely redistributing the Usage of the Grid.
- In summer, there are almost 100% of relative CO_2 savings for 4kW and 8kW PV arrays. The dwelling is self sufficient and additionally supplies the Grid.

Table 3: Relative savings of a dwelling in the UK using the RED WoLF system.

United Kingdom	0 kW PV	2 kW PV	4 kW PV	8 kW PV
spring	21 %	40 %	67 %	91 %
summer	20 %	53 %	97 %	98 %
autumn	22 %	32 %	50 %	59 %
winter	21 %	24 %	29 %	35 %

Be aware that these relative savings are estimates for exemplary scenarios and there are numeral reasons, why the values differ in reality. Firstly, we are calculating with a 100% of efficiency for all the storages, and for the battery. We further compare the CO_2 output to a house, that has no storages and uses the Grid exactly when energy is needed. Compared to a house, that uses the wet heating system instead of the Grid, the savings would be higher again, because of the influence of renewable energy sources in the Grid. One more major point is the difference in storage energy at the beginning and at the end of the simulation. The savings are calculated in comparison to a house that has no storages. To reduce the impact of storage difference, the simulations also start with full storages, because the basic algorithm functions with fully loaded storages. Since several assumptions are necessary, the results are only indicative values by which the efficiency of the system can be measured. Table 4 shows the relative CO_2 savings for scenarios, with the setup of a house in that country with the values from table 4. Note that these results are experimental and will differ in reality, as again the same exemplary CO_2 intensities are used.

Annual Saving	0 kW PV Array	2 kW PV Array	4 kW PV Array	8 kW PV Array
Spain	17 %	26 %	40 %	53 %
Italy	21 %	28 %	38 %	47 %
UK	21 %	27 %	36 %	45 %
Poland	21 %	27 %	36 %	45 %
France	21 %	27 %	36 %	45 %
Germany	22 %	27 %	36 %	45 %
Ireland	22 %	27 %	35 %	43 %
Belgium	20 %	25 %	33 %	42 %

Table 4: Estimates of relative CO_2 savings for different countries and PV array setups.

The higher the consumption of a country, the lower are the relative CO_2 savings of a dwelling. It makes therefore sense to adjust the PV array size to the consumption of the dwelling for a better efficiency.

3 Conclusions

The basic RED WoLF system [Shukhobodskiy and Colantuono], which we introduced in the first chapter, is an important step towards a more sustainable future. Achieving carbon emission reduction secures a more lively environment, and changes the direction our society is heading to. The core purpose of the project is to optimise the power intake, in order to minimise the CO_2 output. Instead of trying to reduce the operation cost or energy consumption, the RED WoLF system achieves significant savings in CO_2 by shifting the energy peak demand to times of low CO_2 Grid intensities. As decarbonisation of the electricity system is an immediate goal of several countries, replacing the wet heating system and using the Grid for heating purposes are important steps to fulfill CO_2 reduction targets and attain independence from fossil fuels.

Finding the adequate threshold, which serves as an indicator to change the energy supplier and store heat, is the key feature of this algorithm. It is worth noticing that thermal demand is not to be satisfied with the battery output, due to conversion losses and relatively large amount of energy required for heating. In addition, the cost of thermal storage is significantly lower than what we would need for the constant battery use. The standard configuration of the system, with a 4kW PW array and a 10kWh battery installed, offers us drastic CO_2 savings, ranging from 30% up to 98% during the summer.

In the second chapter we presented generalised version of the RED WoLF system, which creates stable scenarios for 8 days. It serves as an example that the system is sustainable for multiple days (as in [Shukhobodskiy and Colantuono]). The algorithm can be further modified to increase efficiency in different regions, as there are differences in the maximum rate of house intake. With the mentioned changes, we were able to apply the algorithm to various European regions. It turns out that adjusting the loading sequence for the storages can save an additional 1 to 2 percent of CO_2 emissions and should be tested for the specific case.

The simulations performed are based on various assumptions and thus the results are estimates, however they serve as a proof of the RED WoLF's capabilities. In the future, the system can be further optimised as real data is collected in practice. The fact that the cost of electrical energy usually follows the CO_2 intensity levels introduces an alternative motive for pursuing changes the RED WoLF offers. Namely, the benefit of the system is therefore not only the reduction of CO_2 emissions, but also the decrease of the heating cost, which accounts for more than 10% of the household income in certain regions [Hartley, 2019]. As the number of renewable energy providers supplying the Electric Grid increases, the system also stabilises the Grid. Overall, it can be said that the system has numerous advantages and is in many ways superior to traditional heating systems.

4 Group work dynamics

We started by making basic plots which would help us understand the code and how the system works. The plotting function created on the first day was also used daily afterwards. After understanding the principles of the RED WoLF system, we started to enhance the simulation step by step. At first, we made the simulation work for two consecutive days, then we added demands for heat and hot water and implemented methods to create a stable algorithm that worked for eight days eventually. After that, we adjusted the algorithm to work for different environments, and polished everything.

While the computational engineer Michael Wiesheu was usually responsible for implementing changes in the code, the applied mathematicians Luka Rutešić and Gennesaret Kharistio Tjusila did important decision making, and were responsible for finding logical errors. The work was evenly distributed among the researchers, who invested a considerable amount of time in this elaborate project. Daily meetings were held for several weeks straight, during which the most work had been done. Occasionally guided by the mentor Dr. Alexander Shukhobodskiy, impressive results were accomplished.

The most challenging part of the group work has been synchronizing the time tables and schedules, however it did not impede our project. Since only three people were involved, the distribution of roles was clear and the organisation did not impose a major problem. The preparation of the final report was demanding from time to time, as everyone had different ideas to contribute and how to organise the content. The report was mostly done by another week of daily work.

5 Instructor's assessment

The main goal of the project was to create an algorithm which generalises the basic version of the RED WoLF procedure. There were 2 targets which students achieved within proposed time frame and created a better version of ready to go product. Furthermore students considered different possibilities of the RED WoLF for different countries.

The project could be separated into two main categories. The first one is assessment of the RED WoLF basic algorithm and the second stage is algorithm modification and numerical simulations. At the initial stage the group showed excellent ability to absorb new material, which has later resulted in carefully vetted proposals for system modification and at the stage of numerical simulation. The new system was able to improve the initial RED WoLF basic algorithm, showing the brilliance and professionalism of the group working on the project. Furthermore, the system behavior was simulated for different environments and additional changes to the procedures. Such a milestone is paramount for the scientific community. Thus the result of the group work not only showed the diligence and exceptional professionalism of the group but also exceeded initial expectations from the project. As an instructor the work with the group was of a great satisfaction and pleasure, which built an excellent relationship for future collaborations and continuation of work.

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