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# Agent-based Modeling for Optimizing CO<sub>2</sub> Reduction in Commercial Greenhouse Production with the Implicit Demand Response

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Industries are identified as major potentials to reduce the CO<sub>2</sub> emission due to their large energy consumption and the possibility of providing energy flexibility with optimization and smart control. Commercial greenhouses are considered as one of the industries that have large energy flexibility potentials with the heavily used artificial lighting (around 75% of the electricity consumption coming from artificial lighting). This paper investigates the CO<sub>2</sub> reduction potential in the commercial greenhouses with a case study of the Danish commercial greenhouses via participation in the implicit Demand Response. Agent-Based modeling is used to simulate the greenhouse production and the response to the electricity spot price signals. The result shows that the potential of CO<sub>2</sub> reduction in 2018 was 0.33% (equals to 170 thousand tonnes) of the total Danish emission when 50% (equals to 181 growers) of the Danish commercial greenhouses participate in the implicit Demand Response. The last 50% of the commercial greenhouses have a relatively slow adoption rate and account for only a small amount of CO<sub>2</sub> reductions. Meanwhile, the largest reduction of the CO<sub>2</sub> emission is not in chronological order as commercial greenhouses' financial saving because the electricity spot price and solar irradiation do not follow each other.

**Keywords:** Agent-based modeling, implicit demand response, commercial greenhouses, CO<sub>2</sub> emission, electricity generation mix

## 1. Introduction

One of the biggest factors in the global warming is the greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O), and the Paris Agreement The Paris Agreement involved 181 parties aims to keep the temperature increase limited to 1.5 °C above pre-industrial levels<sup>(1-3)</sup>. One of the acts in achieving this goal is to reduce the pollution of greenhouse gasses, especially carbon dioxide (CO<sub>2</sub>) in the energy sector because the largest share of CO<sub>2</sub> emission is produced in the energy sector<sup>(4)</sup>.

The European Union (EU) has conducted initiatives to meet the urgent need for reducing CO<sub>2</sub> emission, e.g. a CO<sub>2</sub> quota system called the "European Union Greenhouse Gas Emission Trading System"<sup>(5)</sup> in Europe. One of the European countries, Denmark is a pioneer in sustainable energy development and aims to be fossil independent by 2050. Already in 2030, all produced electricity in Denmark should come from renewables<sup>(6, 7)</sup>. This means that larger shares of renewables such as wind and solar are presented in the Danish electricity generation mix. In 2017, the shares of wind and solar energy correspond to 45.8% (wind: 43.4% and solar: 2.3%) of the total Danish electricity production<sup>(8)</sup>. As wind and solar energy vary in accordance with weather, and also vary the structure of the Danish electricity generation mix.

A low share of renewable energy due to the weather conditions can be compensated by a larger share of fossil-based fuels. This can result in a larger CO<sub>2</sub> emission for the hours with e.g. low wind energy. Hence, the CO<sub>2</sub> emission per kWh electricity can

vary from hour to hour and country to country, as the generated CO<sub>2</sub> emission is dependent on the electricity generation mix. Electricity production units have different emission factors based on their fuel type. The United Nations' Framework Convention on Climate Change defines an emission factor as the average emission rate of a given greenhouse-gas for a given source, relative to units of activity<sup>(9)</sup>. For example, natural gas emits approximately 0.2 kg CO<sub>2</sub>-eq/kWh<sup>(10)</sup>.

Even though a global share of renewables in the electricity generation mix is increasing, there are challenges for the green transition and keep the temperature raise stay below 2°C<sup>(11)</sup>. Beukel<sup>(12)</sup> states four challenges to reduce the CO<sub>2</sub> emission, and one is 'The benefit of reducing CO<sub>2</sub> emission is global and long term. However, the associated costs are local and short term'.

Therefore, an efficient way to support the CO<sub>2</sub> emission reduction in the electricity sector should not involve heavy investments in the grid expansion and electricity storage installation, but to apply smart energy solutions with the participation of Demand Response (DR). DR is defined by the European Commission as voluntary changes in consumers' electricity usage patterns – in response to market signals<sup>(13)</sup>. The participation of DR has the potential to reduce CO<sub>2</sub> emissions because of peak hours that has the highest electricity prices include a large share of fossil generation such as coal and natural gas. Electricity production units running on natural gas and coal are expensive compared to wind and solar<sup>(14)</sup>. Hence, participating in implicit DR will avoid peak hours and, in most cases, result in a reduction in CO<sub>2</sub> emissions.

This paper aims to investigate the possible CO<sub>2</sub> emission reduction by simulating commercial greenhouses' adoption towards implicit DR. Commercial greenhouses are chosen for a case study as greenhouses have a huge electricity consumption coming from artificial lighting that is suitable for participation in implicit DR.

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This paper is part of a research project with an overall research question of ‘How do the characteristics of implicit DR enabled software solutions affect commercial greenhouse growers’ participation in implicit DR programs?’ The following hypotheses are designed to answer the research question.

- If the adoption rate depends on the Return on Investment (ROI) time, then a shorter ROI time will increase the adoption rate.
- If the initial cost for adoption is proportional to the ROI time, then an increase/decrease in initial cost will extend/shorten the ROI time with the same factor.
- If the electricity price structure affects the adoption rate, then an increase/decrease in tariffs and levies will shorten/extend the adoption time.
- If the type and size of the commercial grower market are the same, then weather and electricity price structure affect the adoption rate that more/less sunlight and higher/lower electricity price will adopt faster/slower.
- If the CO2 emission from consuming electricity depends on the electricity generation mix, then consuming electricity in cheap hours will reduce CO2 emissions.

This paper focuses on the last hypothesis and the perspective of CO2 reduction. The paper is organized by firstly introducing the research background providing the background knowledge behind the research. Secondly, Section 3 explains the simulation design and development. Thirdly, the case study is described followed by the results and discussion in Section 4 and 5. Lastly, the conclusion is conducted in Section 6.

## 2. Research Background

### 2.1 Electricity Generation Mix & Electricity Spot Price

Energy-intensive industries account for a large CO2 emission based on their large energy consumption. As mentioned earlier, the CO2 emission from the consumed electricity varies throughout the whole day because the electricity generation mix varies. Hence, moving electricity use from hours with a large share of energy production with fossil-fuel to hours with more renewable energy sources can reduce the CO2 emission. It can be achieved via participation in the implicit DR program. DR is represented by two overall approaches called implicit- and explicit DR. Implicit DR is consumers being exposed to time-varying electricity prices that reflect electricity prices in different time periods. This program, therefore, does not allow consumers to participate alongside generation in the electricity markets <sup>(15, 16)</sup>. Whereas, the explicit DR is a program that gives the end-users the possibility to compete in the wholesale market with producers, balancing and ancillary services. This, however, is only possible through aggregators or if the consumer is large enough <sup>(15, 16)</sup>. Today, Denmark does not allow independent aggregators which is why this paper only investigates business opportunities for implicit DR.

The electricity price signals are from the electricity spot market (the wholesale market). For instance, in the Nordic electricity spot market, the electricity spot price is based on the most expensive production unit as the price and is decided by the merit order dispatch <sup>(17)</sup>. Therefore, hours with cheap electricity typically mean that the share of renewables is high as they are the cheapest production units. However, this is not always the case because many factors can affect this result, such as the import/export of electricity as shown in Fig. 1 (a) and (b). The figures are created with data accessible from <sup>(18)</sup> and <sup>(19)</sup>.

Fig. 1 (a) and (b) illustrate that the CO2 emission does not

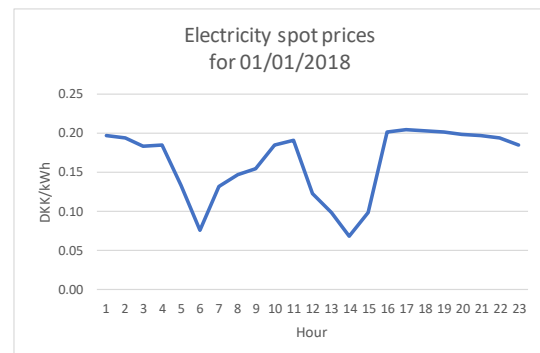
always follow the spot prices. Therefore, by optimizing the electricity consumption in regard to the largest saving does not mean the highest reduction of the CO2 emission. In many cases, the CO2 emission remains constant even though the spot price decreases. For example, the cheap wind energy replacing the expensive biomass production can reduce the electricity price but keeps the same CO2 emission level as none of them emits CO2. However, moving energy consumption to cheap hours, in most cases, can reduce CO2 emission and give the energy users an economic incentive to change their energy usage behavior.

### 2.2 Danish Commercial Greenhouses

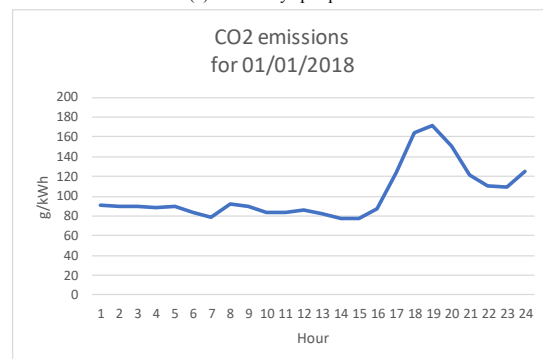
The Danish Energy Agency states that energy-intensive industries are suitable candidates for changing their electricity schemes to respond to fluctuating electricity prices <sup>(20)</sup>. According to <sup>(21)</sup>, industries that have high potentials to provide energy flexibility are foundries, cold stores/refrigeration companies, dryers, industrial furnaces, greenhouses, street lighting, air-conditioning/ventilation, electric heating, and large IT systems. Energy flexibility is the ability to increase or reduce the production of power plants or the consumption of demand processes <sup>(22)</sup>.

This paper focuses on commercial greenhouses due to their large energy consumption and energy flexibility potentials. In 2017, the energy consumption by commercial greenhouses corresponds to 0.7% of the total Danish consumption <sup>(23, 24)</sup>. 75% of this consumption is estimated from artificial lighting <sup>(25)</sup>. Commercial greenhouses can participate in DR with the adjustment of the artificial light because the artificial light can be applied to the plants in hours where electricity is cheap.

However, it is important to keep the production requirements,



(a) Electricity spot prices.



(b) CO2 emissions.

Fig. 1. Electricity spot prices and CO2 emissions for January 1, 2018.

not to affect the plants' growth. Days with sufficient natural light reduce the possibility for greenhouses to participate in DR programs. The reason for this is that greenhouses' energy flexibility comes from their artificial lighting that is unnecessary at a high level of natural light. Therefore, commercial greenhouses' energy flexibility potential is weather dependent. It is possible to plan the daily lighting schedule at the lowest possible electricity prices and still meet the minimum light and dark hours requirements. That can be done by using weather forecasts and electricity prices for the next 24 hours <sup>(26)</sup>. The participation of DR programs allows the greenhouses to utilize their potential energy flexibility and results in saving of the electricity cost. The saving is an incentive to trigger commercial greenhouses to participate in the implicit DR program and this participation can have an effect on the reduction of the CO<sub>2</sub> emission.

### 3. Methodology

**3.1 Agent-Based Modeling Design** This paper designs agent-based modeling with a definition of the adoption behavior of commercial greenhouses. The adoption behavior is the decision to participate in the implicit DR that effects on the CO<sub>2</sub> emission from the consumed electricity. The agents of commercial greenhouses are implemented in a defined environment representing the Danish commercial greenhouses' electricity system. The simulation is conducted in a software tool called Anylogic. Anylogic features system dynamics, discrete events, and multi-agent methods <sup>(27)</sup>. Agent-based simulation is a suitable modeling method for simulating complex systems such as energy systems, business ecosystems, and consumers' adoption behavior <sup>(28-31)</sup>. To participate in the implicit DR, the data of the electricity spot price and solar irradiation is included in the modeling. The included data is a 24-hour forecast data (see example in Fig. 2 (a) and (b)) and a 24-hour light management schedule. The light schedule is based on the calculation of the photosynthesis gain provided by the artificial light at the lowest spot price. The plants' growth requirements are held at all times. The photosynthesis gain as function to the solar irradiation is non-linear as evident in Fig. 3. The function assumes a constant leaf temperature of 25 °C and a constant CO<sub>2</sub> level of 400 ppm. Taking this function and its non-linearity into account the plant's growth at the lowest price is optimized. For instance, providing artificial light to plants at night, in most cases, can be preferable as it gives the highest photosynthesis gain. Furthermore, the amount of natural light applied during the days from the forecast is considered in the modeling. This means that the artificial light is not turned on if the forecast has enough natural light to reach the plant's daily light sum. The plant's daily light sum is the amount of light that the plant requires to have optimal growth and depends on the plant's species. The plants need "dark hours" that are necessary for plants to respire and complete the photosynthesis cycle. The dark hours are from 5 PM to 12 midnight. This information including the necessary installed light power for each plant species is provided by a plant expert, Prof. Carl-Otto Ottosen, Department of Food Science, Aarhus University and Knud Jepsen A/S (large commercial greenhouse in Denmark). From this information and statistics of the Danish commercial greenhouse growers (The statistics are provided by Statistic Denmark the national authority on Danish statistics <sup>(32)</sup>), an agent population representing the Danish commercial greenhouses is created for the agent-based modeling.

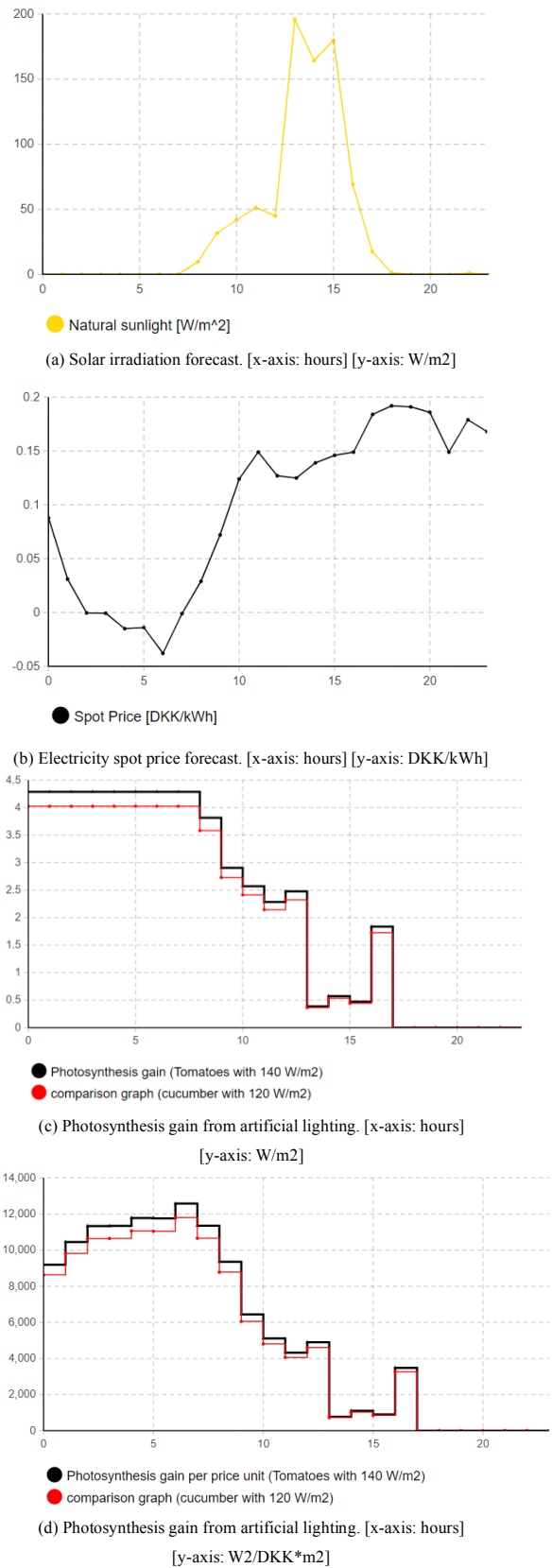


Fig. 2. Simulation curves illustrating forecasts used in operating lighting in new solution. All graphs are for the 1<sup>st</sup> of March 2015.

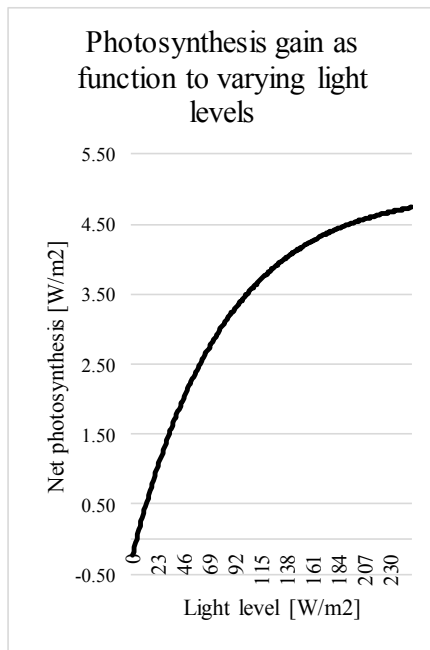


Fig. 3. Photosynthesis as a function of solar irradiation adapted from <sup>(26)</sup>.

**3.2 Agent Population and Simulation Design** The population is based on the greenhouses' plant species, installed light power, light sum, and size <sup>(33)</sup>. The agent set up in the model is shown in Fig. 4. The figure shows a screen dump of the simulation before running. 1) Prints the reduced CO2 emission; 2) Buttons created to enable quick scenario changes; 3) Sliders for changing the initial investment for adopting the implicit DR, leaf temperature and CO2 concentration; 4) Electricity price components for Denmark. Only the CO2 emission count button is used in the model for this paper's simulation. This button sets up the simulation to count the reduced CO2 emission and shows them at 1). Fig. 2 (c) and (d) illustrate the photosynthesis gain and photosynthesis gain divided by the spot price, respectively. These two figures also include a red curve to illustrate the non-linearity as the space between the black and red curves are biggest at night. The comparison of Fig. 2 (c) with (a) shows how natural light affects the photosynthesis gain by the artificial light. Meanwhile, the comparison of Fig. 2 (d) with (c) and (b) shows that the spot price affects the curve and the optimal hour to provide artificial light is at 6 AM on the given day. Without the consideration of response to the electricity spot price signals, the commercial greenhouses usually manage their light based on real-time light measurements. The artificial light is turned on from 12 midnight and stays on until the plants' light sum has been reached. The artificial light is turned off when the natural light is sufficient. The setpoint light is specified by the types of plants, for instance, 140 W/m2 for tomatoes. In the previous research <sup>(33)</sup> the model investigates the allowed maximum adoption cost when 50% of the commercial greenhouses adopt within five years. 50% is chosen based on Roger's adoption curve that the adoption rate peak happens at 50% <sup>(34)</sup>. The application of Roger's adoption curve in the research is explained in detail in <sup>(33)</sup>. In the previous research <sup>(33)</sup> and this paper, the greenhouses' adoption is triggered when the financial savings equal to the adoption cost.

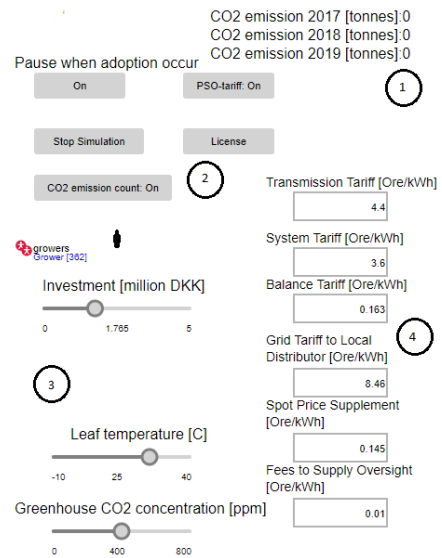


Fig. 4. Parameters of the agent in the designed model.

#### 4. Case Study

This paper focuses on the reduction of the CO2 emission by the commercial greenhouses' electricity consumption with the adoption of implicit DR participation. The agent population consists of 362 commercial greenhouses in Denmark (the number is based on the information from the Statistics Denmark). The reduction of CO2 emission from 2017 to 2019 is examined and analyzed. The reduction of CO2 emission is to be found with two scenarios: 1) when the first half of the commercial greenhouses participate in the implicit DR program, 2) when all of the commercial greenhouses participate in the implicit DR program in Denmark. The first half of the commercial greenhouses participate in the implicit DR program is defined based on the significance of the monetary savings with the participation in the implicit DR program. The hourly CO2 emissions for the modeling is provided by the Danish TSO (Transmission System Operator)- Energinet. The data is illustrated in Fig. 1 (b) for 24 hours.

The CO2 emission data is available from 2017. Therefore, the modeling only uses data until October 31, 2019, and the reduction of the CO2 emission found for 2019 is multiplied by 1.2 to account for the missing 2 months. As the data is for each 5 minutes and the electricity spot price is hourly, the hourly average CO2 emission is calculated to represent the hourly CO2 emission in the modeling.

The CO2 emission data is calculated from the electricity generation mix in the given moment. Each generation unit has a certain emission factor. Emission factors for chosen fuels can be seen in Table 1 <sup>(35)</sup>. The CO2 emission in the data represents CO2 equivalents accounting for all greenhouse gases. Furthermore, the data accounts for imported/exported electricity, production of heat at Combined Heat and Power (CHP) plants, and loss in transmission and distribution grid. The method used to account for the heat production is called the 125%-method and assumes that the efficiency for converting the fuel to heat is 125% <sup>(36)</sup>. The import/export of electricity between countries is accounted for by using the electricity generation mix for the country importing from <sup>(36)</sup>. For instance, the calculated yearly average sizes of the CO2 emission are 227.89, 202.99, and 170.76 g/kWh for 2017, 2018, and 2019, respectively.

Table 1. CO2 emission factors.

Fuel	Emission Factor [tonnes CO2/TJ]
Natural Gas	56.89
Dieseloil	74.1
Coal	94.6
Waste	42.5
Fueloil used in combined heat and power plants	79.19

## 5. Results and Discussion

The results of the simulation are shown in Table 2 and Table 3. Table 2 shows the total reduction of CO2 emission if all of the commercial greenhouses participate in the implicit DR program. The differences in CO2 reduction from the greenhouse production process is caused by several factors. One factor is that the greenhouses' operation of light is weather dependent, therefore, it varies from year to year. Another factor is that more wind- and less fossil energy was produced in 2017 than 2018<sup>(37)</sup>, and wind energy produces less CO2 compared to fossil fuel. Hence, the CO2 reduction from the consumption side varies based on the electricity generation mix from year to year. Table 3 has listed the CO2 reduction for each of the first 50% commercial greenhouses adopting the implicit DR from 2017 to 2019.

The comparison of the two tables shows that the difference between the total reduction of the CO2 emission and the first 50% commercial greenhouses is small. This means that the reduction of the CO2 emission with the last 50% of the commercial greenhouses is relative small. Meanwhile, the largest reduction of the CO2 emission is not in chronological order after when commercial greenhouse adopts the implicit DR program participation. The reason is that the electricity spot price and solar irradiation do not follow each other (as shown in Fig. 1 (a) and (b)), and the adoption rate of the implicit DR program participation depends on the amount of monetary savings. The last 50% of the commercial greenhouses have a relative slow adoption rate and account for only a small amount of CO2 reductions. Hence, achieving 50% adoption results in the highest CO2 reduction relative to the adoption rate. In 2018 the total Danish CO2 emission was 51.9 million tons<sup>(37,38)</sup>. A potential reduction of 0.33% of the total CO2 emission was achievable if the first 50% of the greenhouses participate in the implicit DR program.

It was found that in several hours during the year, the greenhouses increased the CO2 emission by adopting implicit DR. As mentioned earlier in relation to Fig. 1, the CO2 emission per kWh do not behave in accordance with the spot price. However, the total CO2 emission is still reduced because the emission in many cases is lower in expensive hours than in cheaper hours. Furthermore, the new solution allows the system to know the natural light beforehand. Hence, in many cases electricity consumption is reduced instead of moved to cheaper hours and this will always reduce CO2 emission. Therefore, the hypothesis is rejected as the CO2 emission not always is reduced when moving consumption from expensive hours to cheaper hours.

The reduction of the CO2 emission is necessary for Denmark and other countries to reduce climate change. A solution could be adding taxes on the CO2 emission. This will increase the potential monetary savings with the participation in the implicit DR programs. If the European Union can apply the CO2 quota system

Table 2. The reduction of CO2 emission with 100% commercial greenhouses participate in implicit DR program

Total Saved CO2 in 2017 [tonnes]	168,804
Total Saved CO2 in 2018 [tonnes]	170,313
Total Saved CO2 in 2019 [tonnes]	124,033

Table 3. The CO2 emission reduction with the first half of the commercial greenhouses participate in the implicit DR program

Plant species	Greenhouse segment [m2]	Saved CO2 in 2017 [tonnes]	Saved CO2 in 2018 [tonnes]	Saved CO2 in 2019 [tonnes]
Pot plants	>20,000	74,640.2	75,253.78	54,644.64
Tomatoes	>20,000	18,313.5	18,629.04	13,672.32
Cucumber	>20,000	21,554.3	21,711.80	15,850.78
Herbs	>20,000	3,669.85	3,695.78	2,691.30
Pot plants	15,000-19,999	5,507.86	5,553.14	4,032.35
Salad	>20,000	922.59	914.91	669.61
Salad	15,000-19,999	830.33	823.41	602.66
Tomatoes	10,000-14,999	5,232.43	5,322.58	3,906.38
Cucumber	10,000-14,999	2,300.47	2,317.28	1,691.75
Pot plants	10,000-14,999	10,736.6	10,824.82	7,860.34
Herbs	10,000-14,999	1,983.76	1,997.78	1,454.80
Salad	10,000-14,999	922.59	914.90	669.62
Tomatoes	5,000-9,999	1,283.53	1,305.64	958.24
Pot plants	5,000-9,999	11,403.1	11,496.90	8,348.31
Cucumber	5,000-9,999	1,150.24	1,158.64	845.87
Herbs	5,000-9,999	1,076.19	1,083.79	789.23
Pot plants	2,000-4,999	6,466.91	6,520.05	4,734.50
<b>Total</b>		<b>167,994</b>	<b>169,524</b>	<b>123,423</b>

to energy-intensive industries, a faster reduction of CO2 emission can be achievable as the monetary incentive for DR participation will be larger.

## 6. Conclusion

This paper investigates the potential reduction of the CO2 emission of the commercial greenhouses with the participation in the implicit demand response. Agent-Based modeling is used in the paper to simulate the commercial greenhouses production with the usage and adjustment of artificial lighting with two scenarios.

The reduction of the CO2 emissions with the data for 2017, 2018 and 2019 is examined in the modeling. It finds that a reduction of 0.33% (equals to 170 thousand tonnes) of the total Danish CO2 emissions in 2018 was achievable with a 50% (equals to 181) of the commercial greenhouses participating in the implicit demand response. The total reduction of the CO2 emission by the last 50% of the commercial greenhouses is relatively small. Therefore, the identified first 50% the commercial greenhouses are more suitable for achieving a large reduction of the CO2 emission at a faster rate. Applying taxes for the CO2 emission on electricity consumption may increase the monetary incentive for large energy users to adopt more energy-efficient solutions.

The hypothesis 'if the CO<sub>2</sub> emission from consuming electricity depends on the electricity generation mix, then consuming electricity in cheap hours will reduce CO<sub>2</sub> emissions.' is rejected. The rejection is based on several hours where moving electricity consumption from expensive hours to cheaper hours resulted in higher CO<sub>2</sub> emissions.

Some data used in this study was limited accessible, e.g. historical CO<sub>2</sub> emissions before 2017. Future work of more detailed greenhouse statistics and light operation for all types of greenhouses is recommended. Meanwhile, taxes on CO<sub>2</sub> emissions are considered in many countries, therefore, this paper suggests further research take taxes on CO<sub>2</sub> emissions into consideration to simulate the impact on the adoption rate and potential CO<sub>2</sub> emission reduction.

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