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Agent-based Modeling of Climate and Electricity Market Impact on Commercial Greenhouse Growers' Demand Response Adoption

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***Abstract*— Commercial greenhouses in Denmark account for 0.7% of the total Danish electricity consumption in 2017. 75% of the consumption is estimated to come from artificial light. Artificial light in the greenhouses is identified as a major potential to provide energy flexibility through demand response. Energy flexibility in greenhouses is depending on the electricity price and weather conditions as artificial light is managed in relation to natural light and hourly electricity prices. Therefore, this paper investigates commercial greenhouse growers' adoption behavior of implicit demand response enabled software solutions in different geographical regions with different weather conditions and electricity markets. The simulation of the greenhouses is developed as an agent-based system. The paper uses Denmark as the baseline model, the UK for market comparison with Denmark, and Spain and Denmark for analyzing the adoption rate's sensitivity to solar irradiation. The results reveal that higher electricity prices and more solar irradiation result in faster adoption and the adoption rate is more sensitive to electricity price than solar irradiation.**

Keywords—Agent-based modeling, demand response, commercial greenhouses, technology adoption, solar irradiation, electricity price

I. Introduction

Energy systems are under the green transitions around the world due to climate goals and agreements such as the Paris agreement in 2015 [1]. In relation to this many new technologies and innovations are introduced to the energy markets. Currently, the failure rate to launch new product/solution to the market is high, the smart energy solutions usually require large investment [2, 3], and the market adoption rate and growth speed is slow and depends on different market segment and business models that companies apply [3, 4]. A reason for this is that many smart energy solutions replace existing technologies which are not considered green. From the consumers' perspective, this involves a cost which, as illustrated in Fig. 1, is added to the purchase price of the new solution. Furthermore, the figure illustrates what the innovator sees and includes only the purchase price. Therefore, to avoid the risk and predict the market reaction, this research applies agent-based simulation to find the adoption rate of implicit demand response (DR) enabled software solutions for commercial greenhouses. The Danish commercial greenhouse growers are selected in the study because the Danish commercial greenhouses' electricity consumption accounts for 0.7% of the total Danish consumption in 2017 [5, 6]. 75% of the consumption is estimated to come from artificial lighting [7].

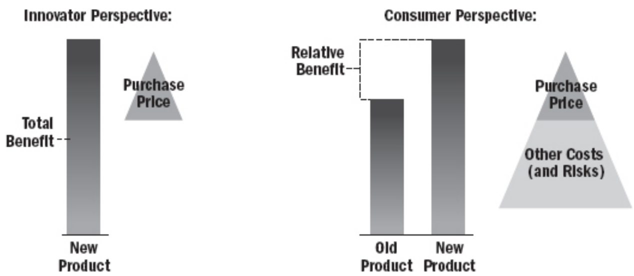

Fig. 1. The consumer and innovator's perspective of "benefits" and "costs" [8].

This paper is a part of a research that aims to investigate commercial greenhouses adoption towards implicit DR software solutions. More about the research can be found from [9]. The research question for the overall research is: *How do the characteristics of implicit demand*

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response enabled software solutions to affect commercial greenhouse growers' participation in implicit demand response programs?

Four hypotheses are designed to answer the research question:

1. If the adoption rate depends on the Return On Investment (ROI) time, then a shorter ROI time will increase the adoption rate.
2. 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.
3. If the electricity price structure affects the adoption rate, then an increase/decrease in tariffs and levies will shorten/extend the adoption time.
4. 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.

This paper focuses and investigates the fourth hypothesis by comparing the Danish commercial greenhouse growers' adoption rate with the UK and Spanish markets by changing weather and electricity data inputs.

Agent-based modeling is an artificial intelligence method to simulate real-life systems compared to system dynamics and discrete event modeling. Agent-based modeling allows finding the system behavior, with the possibility of applying several agents in an environment that interact with each other (multi-agent-based modeling). There is no direct definition for an agent, but agents can represent many different things in an agent-based model like vehicles, projects, products, people in different roles, ideas, investments, etc. [10]. Agent-based modeling offers a flexible architecture that allows a detail representation of complex agent systems, including the agents' behaviors, their interactions, physical and economic environments around them [11]. Examples for such systems could be energy systems and consumers' adoption behavior of new smart energy solutions [12, 13].

Therefore, the overall research applies agent-based simulation to investigates commercial greenhouse growers' adoption behavior of implicit demand response enabled software solutions in different geographical regions with different weather conditions and electricity markets. The paper uses Denmark as the baseline model, the UK for market comparison with Denmark, and Spain and Denmark for analyzing the adoption rate's sensitivity to solar irradiation.

The paper is organized as follows: firstly, the research background is introduced; secondly, the simulation design is described followed by an explanation of the case study. Results and discussion are presented with the conclusion in the end.

II. Research Background

To design a model that can simulate the greenhouses' behavior in a given environment, this paper firstly identifies the Danish commercial greenhouses' electricity business ecosystem (shown in Fig. 2) to better understand the real system [14]. Fig. 2 also illustrates the data, payment, and product flows that visualize the different stakeholders' roles in the ecosystem [15].

The Danish commercial greenhouses' electricity business ecosystem is described with the numbers in Fig. 2:

1. The Distribution System Operators (DSOs) send metered data and information about tariffs and other price elements to the DataHub.
2. The Transmission System Operator (TSO) provides the TSO tariffs to the DataHub.
3. DataHub can then provide metered data and tariffs for each metering point to the electricity suppliers.
4. The electricity suppliers receive one single payment including all tariffs and taxes from consumers. The supplier pays all taxes, tariffs, subscriptions, and fees for the consumers to the government, DSO and TSO.
5. The Balance Responsible Parties (BRPs) receive payment for electricity from the electricity suppliers which is used to pay the electricity producers.

Many factors are taken into consideration when consumers adopt an innovation or technology, such as relative advantages (e.g. economic profitability), compatibility, complexity, trialability, and observability [16].

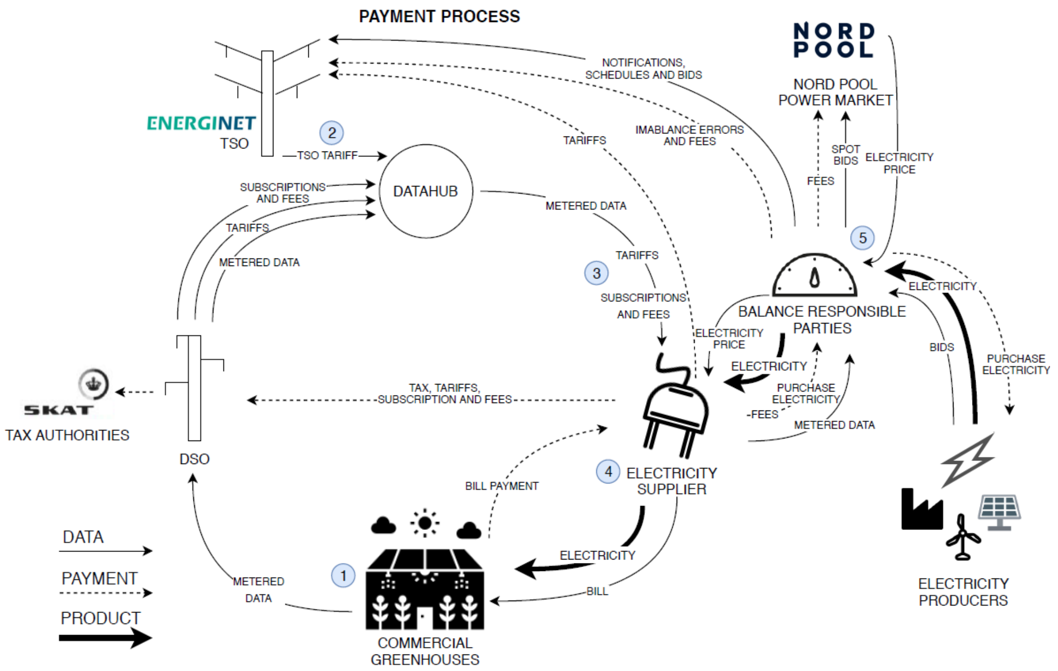

Fig. 2. Commercial greenhouses' electricity business ecosystem, adapted from [17].

The factors that influence the adoption rate need to be considered for the investigation of the market reaction towards an innovation. The adoption rate is used for measuring how different business opportunities influence the adoption of a new solution. However, this study only investigates the relative advantages in the form of economic benefits. Furthermore, Roger's adoption curve theory is used to identify the innovators (the fastest adoptor) of the greenhouse population [7]. The curve is shown in Fig. 3.

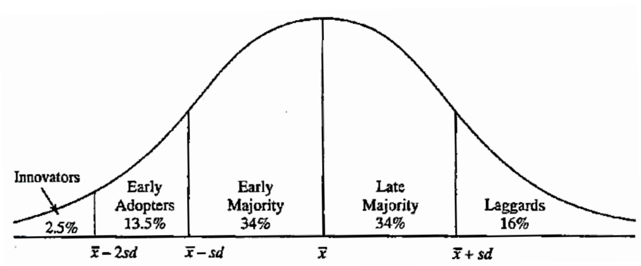

Fig. 3. Rogers' adoption curve with adopter categorization.

DR is defined by the European Commission as voluntary changes in consumers' electricity usage patterns – in response to market signals [18]. DR programs aim to incentivize changes in the electricity consumption patterns in response to the varying electricity prices or incentivize payments to lower electricity consumption at times with high market prices [19]. DR can be divided into two main categories: explicit and implicit.

Explicit DR allows end-users to compete in the wholesale market with producers, balancing and ancillary services. This is possible with services provided by aggregators or single large consumers. Aggregators trade aggregated load in the electricity markets, receive payment comparable with the generation, and consumers receive direct payment in the explicit DR [19, 20].

Implicit DR is when consumers are being exposed to time-varying electricity prices that reflect the electricity price in different time periods. These prices are agreed beforehand as part of their electricity supply contract. Therefore, implicit DR does not allow consumers to participate alongside generation in the electricity markets [19, 20].

The commercial greenhouse sector has a large potential in participating in a DR program. Commercial greenhouses have a large electricity consumption from artificial lighting used in plant production. Especially in Denmark that has few hours with natural light during wintertime. The light schedule management, to some extent, can be changed as long as the requirements for the plant's growth is kept [21]. Some literature has earlier investigated the DR in commercial greenhouses and the adoption of smart grid adoption [22, 23]. [24, 25] investigates influential factors that have an impact on industrial consumer's adoption of smart grid solutions. [25] identifies greenhouses as a potential flexible energy consumer but does not use it in any further study. [11] provides an overview of agent-based modeling that works in the area of consumer energy choices. The paper explains the advantages of using agent-based modeling in the simulation of energy systems. The paper focuses on energy consumers because standard models of energy systems include detailed representations of energy suppliers with relatively less attention to the complexities of consumer demand. The research of [26] and [27] uses agent-based modeling for the investigation of energy savings in commercial buildings and market efficiency in electricity systems. The agent-based model in [26] includes adoption rates for technologies competing in a virtual marketplace and the model is developed by a multi-agent modeling software tool called *RePast*. However, none of them is investigating commercial greenhouses.

III. Simulation Design

The agent-based model is developed in the software tool *AnyLogic*. AnyLogic is a unique simulation software tool that supports three simulation modeling methods: system dynamics, discrete event, and agent-based modeling and allows you to create multi-method models [28].

In this research, the simulation includes an agent population of 362 Danish commercial greenhouses. The population is based on categories for the greenhouse growers' plant types and the sizes of the greenhouses with artificial light. These population divisions are chosen as the different plant species have different needs in light, hence the greenhouses use different power levels for the light. For example, according to a plant expert, Prof. Carl-Otto Ottosen, Department of Food Science, Aarhus University, tomatoes and cucumbers require 140 and 120 W/m2, respectively. The population was created based on 2017 statistics for Danish nurseries, collected from Statistics Denmark (the national authority on Danish statistics) [5].

The simulation design is based on a retro-perspective approach using historical data to simulate market behavior. The accumulated electricity cost for the greenhouses with their current operation of the lighting is calculated during the simulation. Meanwhile, the accumulated electricity cost for operating with an implicit DR enabled software solution is calculated and subtracted from the current operation. This is how the savings are calculated and are used to trigger adoption.

The agents' decision trigger is designed to happen when the accumulated saving over time equals the cost of adoption. The simulation finds when 50% of the growers adopt in five years. 50% of market share adoption is, according to Roger's adoption curve in Fig. 3, when the adoption rate begins to decrease. Five years are estimated to be the maximum allowed return on investment time for commercial greenhouses' willingness to adopt.

The implicit DR enabled software solution that utilizes the greenhouses' energy flexibility is a software tool called *DynaLight Desktop*. This solution allows the greenhouse grower to participate in implicit demand response programs. The software provides greenhouse growers with price-optimized supplement light plans [22]. The software considers the day-ahead electricity pricing and creates a plan for operating light in the most cost-efficient way by avoiding high prices and utilize low prices during a 24 hours day.

The software furthermore accounts for the weather, physiological models of plants, and production goals. This allows the software to find a trade-off between energy cost-efficient greenhouse operation and optimal use of artificial lighting to increase plant growth [23]. This is done by calculating the plants' photosynthesis gain from the artificial light and divide it by the spot price in a given hour. This is forecasted 24 hours based on a 24-hour forecast of solar irradiation and spot prices. This way the light will be turned on in the hours that the plants have gained the highest photosynthesis to the lowest price and at the same time keeping the plants' requirements. Fig. 4 shows the interface of a running simulation. Fig. 4, 1) shows the simulation time together with information about the adopting agents' plant type, ROI time, and size (e.g. segment 4: 5,000 to 9,999 m2). 2) are the parameter settings that allow the users to change parameters such as electricity price structure, initial investment cost, removal of PSO-tariff, or changing to a license-based business model. 3) and 4) are the 24-hour forecast of solar irradiation and spot price, respectively.

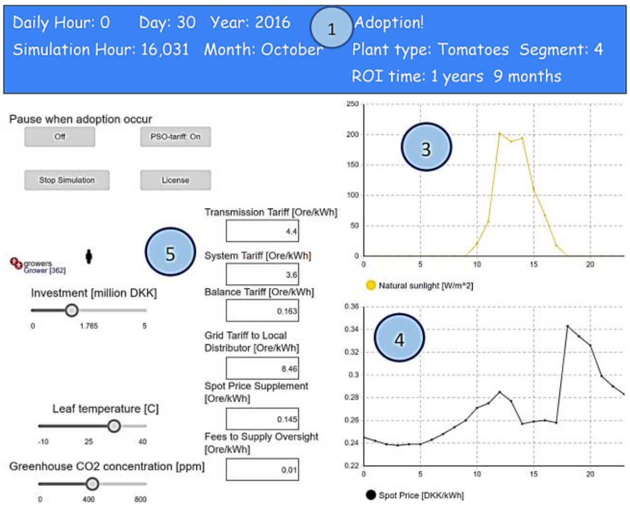

Fig. 4. The interface of a running simulation in AnyLogic.

The photosynthesis gain as a function to the light level is shown in Fig. 5 [29]. The function assumes a fixed CO2 level of 400 ppm and leaf temperature of 25 ºC. The function is non-linear and is the reason why the photosynthesis has to be taken into account. E.g. supplementing the plant with artificial light during daytime can result in a small expensive gain in photosynthesis, even though the spot price is low. The function is used for all plant species in the simulation.

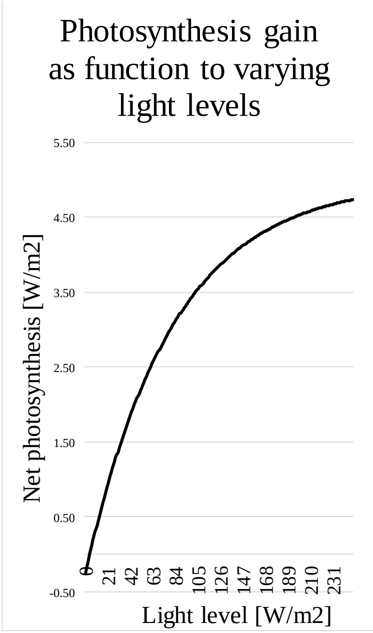

Fig. 5. Photosynthesis function to the light level with constant CO_2 level and leaf temperature.

In this paper, the parameters of interest are solar irradiation, spot price, and the price structure as these vary between countries. The design allows users to change these parameters and investigate their impact on the greenhouses' adoption of implicit DR enabled software solutions.

IV. Case Study

This paper compares the Danish greenhouse growers' adoption with identical growers in the UK and Spain. The weather data for London and the UK electricity price structure and spot price are used to simulate the greenhouses' adoption in the UK market. To investigate the adoption rate's sensitivity to solar irradiation the weather data for Sevilla, Spain is used.

TABLE I shows the electricity price structure for both Denmark and the UK. Notice that the PSO-tariff is not fixed as the PSO-tariff's rate is decided by factors such as electricity production from renewables and average electricity prices. Furthermore, the PSO-tariff is gradually reduced until 2022 where the Danish government has planned to totally removed it from the electricity bill [30]. The model accounts for this change per quarter. However, to give an example of the PSO-tariff's size, the PSO-tariff was in the first quarter of 2015 on 3.14 cents/kWh and 1.4 cents/kWh in the fourth quarter of 2018. As the PSO-tariff is planned to be removed, the simulation will run both with and without the PSO-tariff to see how this affects the markets' comparison.

TABLE I. THE ELECTRICITY PRICE STRUCTURE OF DENMARK AND THE UNITED KINGDOM.

Electricity price structure	
Danish Taxes and Levies [cents/kWh]	***United Kingdom's Taxes and Levies [cents/kWh]***
Spot supplement: 0.02 Fees to supply oversight: 0.0015 Transmission tariff: 0.65 Balance tariff: 0.024 PSO tariff: gradually reduced and removed in 2022 Grid tariff to a local distributor: 1.26 System tariff: 0.54	Network costs: 1.86 Operating costs: 0.32 Environment and social obligation costs: 0.066 VAT: 0.003 Supplier pre-tax margin: 2.29e-5 Other direct costs: 2.87e-7
Total: 2.496 + PSO-tariff	Total: 2.25

V. Results and Discussion

The simulation for the Danish electricity market and weather parameters shows that a maximum initial one-time payment cost of 0.26 million USD for adoption is allowed to achieve a 50% adoption within five years. Fig. 6 illustrates the adoption curve for the Danish market.

TABLE II shows the adopting agent's type and adoption rate as supplement to the adoption curve in Fig. 6. The colors in TABLE II indicates the adoption innovators (green), early adopters (yellow), and early majority (red) reflecting the theory of Roger's adoption curve (Fig. 3).

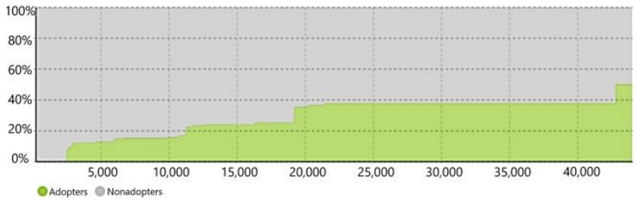

Fig. 6. Adoption curve for the Danish market (50% in five years). [X-axis: Hours] [Y-axis: Market share in percentage].

TABLE II. ADOPTING AGENTS' TYPE AND RATE

Plant type	*Grower segment [m²]*	*Adoption time: years*	*Adoption time: months*	*Adoption time: days*
Pot plants	>20,000	0	3	14
Tomatoes	>20,000	0	3	20
Cucumber	>20,000	0	4	1
Herbs	>20,000	0	6	13
Pot plants	15,000-19,999	0	8	6
Salad	>20,000	0	8	10
Salad	15,000-19,999	0	9	3
Tomatoes	10,000-14,999	1	1	15
Cucumber	10,000-14,999	1	2	22
Pot plants	10,000-14,999	1	3	13
Herbs	10,000-14,999	1	4	6
Salad	10,000-14,999	1	5	9
Tomatoes	5,000-9,999	1	10	10
Pot plants	5,000-9,999	2	2	11
Cucumber	5,000-9,999	2	3	20
Herbs	5,000-9,999	2	5	11
Pot plants	2,000-4,999	4	10	19

A. The Impact of Electricity Price Structure on the Adoption Rate

For the UK market simulation, the price structure was changed in accordance with the structure shown in TABLE I. Besides the structure shown in the table, the varying spot price and solar irradiance data are changed to the UK. It is found that the adoption time increases by 33.95% compared to the Danish parameter settings. In the UK the maximum initial cost is allowed to be 0.20 million USD to achieve a 50% adoption within five years. The adoption curve for 50% adoption in five years is shown in Fig. 7. The order in which the agents adopt is the same as in TABLE II.

The results show that commercial greenhouses identical to those in Denmark adopt slower in the UK than in Denmark. However, when removing the PSO-tariff which is planned to be removed totally from the Danish electricity bill by 2022, the adoption time in Denmark will extend with 2.61 years corresponding to 54.5% compared to when the PSO-tariff is included. This finds that the UK market has a faster adoption rate than in Denmark when removing the PSO-tariff in Denmark. The Comparison of the electricity price structures in TABLE I shows that even without the PSO-tariff, Denmark has the highest taxes and levies. However, the average hourly solar irradiation and spot price for the four years of collected data are 132 W/m2 and 53.8 USD/MWh for the UK. For Denmark, the values are 136 W/m2 and 34.27 USD/MWh. As the solar irradiation values are close to being the same it is conceivably not the factor that influences the large difference in adoption rate. The UK average spot price is found to be 57% higher than the one in Denmark.

As data was limited the data for the UK was found for the years 2013 to 2016 and the Danish data was accessible from 2015 to 2018. From Eurostat (EU's statistics organization) it is found that the raw electricity price in the UK is higher than the one in Denmark [31]. Hence, the difference in years where data is collected is not considered to have a large influence. The results, therefore, show that a higher total electricity price results in a shorter adoption time. The reason, a higher electricity price allows the greenhouses to achieve a higher saving and trigger the adoption earlier. In all cases, it is found that the greenhouses producing pot plants with an area of 20,000 m2 or more will adopt first and will correspond to the innovators in relation to Roger's adoption curve (Fig. 3).

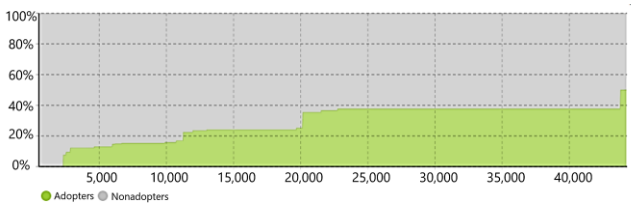

Fig. 7. Adoption curve for the UK market (50% in five years). [X-axis: Hours] [Y-axis: Market share in percentage].

B. The Impact of Weather on the Adoption Rate

It finds that the average solar irradiation data were similar between the selected locations in Denmark and the UK. Therefore, solar irradiation data for Sevilla in Southern Spain has been collected to investigate the impact of the weather at different locations on the adoption rate. The data will replace the solar irradiation data for Denmark and all other parameters are the same. The average hourly solar irradiation for the new data is 214 W/m2 and corresponds to a 57% increase compared to solar irradiation in Denmark. The adoption time is found to be 4 years, 1 month, and 10 days by using an initial cost of 0.26 million USD (the maximum initial cost of 0.26 million USD was found in the Danish market to have a 50% adoption in five years). This is a 16% reduction in adoption time compared to the original weather data from Denmark. Hence, the weather has a great impact on the simulation result. The adoption curve for the simulation using weather data for Spain is shown in Fig. 8.

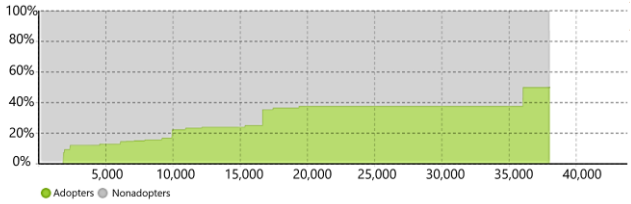

Fig. 8. Adoption curve for weather data for Spain with Danish market parameters. [X-axis: Hours] [Y-axis: Market share in percentage].

To find which parameters the adoption rate is most sensitive to, this paper investigates how large the reduction in the adoption rate is when simulating for the Danish spot prices. The UK electricity spot price is 57% higher than the Danish average spot price. The simulation result shows 50% adoption in 3 years, 8 months, and 17 days with the Danish market and the UK spot prices. This means that by changing from Danish spot prices to the UK prices a reduction of 24% in adoption time is achievable. The adoption curve for using the UK spot prices is shown in Fig. 9. TABLE III shows an overview of the results and indicates that the adoption rate is more sensitive to the spot price than solar irradiation.

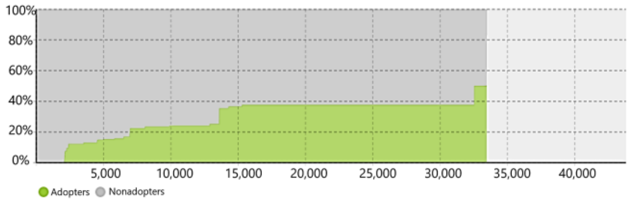

Fig. 9. Adoption curve for the UK spot prices with Danish market parameters. [X-axis: Hours] [Y-axis: Market share in percentage].

TABLE III. SENSITIVITY ANALYSIS OF SOLAR IRRADIATION AND SPOT PRICE: RESULT OVERVIEW.

	Solar irradiation (Denmark-Spain) [%]	*Spot price (Denmark-UK) [%]*
Increased percentage	57	57
Reduction in adoption time	16	24

VI. CONCLUSION

This paper tests the hypothesis of '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'. The study found that the adoption rate in the UK is slower than in Denmark when having the PSO-tariff and faster when removing the PSO-tariff. The reason was found to come from the higher spot prices which were further found to impact the adoption rate more than the solar irradiation. The UK market takes 33.95% longer time for 50% adoption than the Danish market (including PSO-tariff). Furthermore, the UK market is allowed to have a maximum initial cost of 0.20 million USD to have a 50% adoption in five years.

The weather data for Sevilla, Spain was used to find the adoption rate's sensitivity to solar irradiation. Solar irradiation had a great impact on the adoption rate by reducing the adoption rate by 16%. However, the adoption rate is most sensitive to the spot price which reduced the adoption rate by 24%. Thus, the hypothesis is accepted because more sunlight together with higher total electricity prices results in a faster adoption rate.

Furthermore, the innovators of the population of commercial greenhouse growers were found to be pot plant growers with an area of 20,000 m2 or more as Roger's adoption curve states that the first 2.5% of adopters are innovators. In relation to the overall research question, more/less sunlight and higher/lower electricity price will affect the greenhouse growers' participation in implicit DR programs with a faster adoption rate.

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