EUROSUN 2010-SOLAR ENERGY UTILIZATION IN CLOSED GREENHOUSE ENVIRONMENT

Amir Vadiee[1*], Viktoria Martin[1] and Fredrik Setterwall[2]

[1] Heat and Power Technology, Energy department, KTH, Brinellvägen 68, Stockholm, Sweden

[2] Ecostorage Sweden AB, Sollentuna, Sweden

[*] Corresponding Author, Amir.Vadiee@energy.kth.se

Abstract

Closed greenhouses can in principle be free of fossil fuel use if excess solar energy gained is utilized through seasonal storage. In the fully closed greenhouse, there is no ventilation, and the excess heat in the summer can be stored using proper thermal storage system (TES). It can then be utilized later in order to supply heat load to the greenhouse as well as to neighbouring buildings. Although higher amount of solar energy can be harvested through fully closed greenhouse, in reality a semi-closed greenhouse concept is more common. In the semi-closed greenhouse, a large part of the available excess heat will be stored through TES. However, ventilation can still be integrated with TES in order to use fresh air as a rapid response indoor climate control system. The efficient climate control should be integrated with a proper insulation structure in order to minimize the heat loss from the greenhouse and facilitate an accurate indoor climate control system. Based on former studies, it is shown that the grower can control precisely the level of CO_2 in the closed greenhouse, while in open greenhouses; around 90% of supplementary CO_2 is lost due to opening of ventilation windows. This paper presents comparative analysis of heating and cooling demand for an ideally closed greenhouse and a closed greenhouse with infiltration considered. Furthermore, the effective utilization of excess solar energy through the integration of seasonal and short term thermal energy storage is assessed in a first basic design.

Introduction

Closed greenhouse is an innovative concept in sustainable energy management [1]. In principle, it is designed to maximize the utilization of solar energy through seasonal storage. In a fully closed greenhouse, there is not any ventilation window. Therefore, the excess heat must be removed by other means. In order to utilize the excess heat at a later time, thermal storage technology (TES), either long or short term, should be integrated. From previous studies, it has been shown that a closed greenhouse, in addition to satisfying its own heating/cooling demand, can also supply heating and cooling demand to neighbouring buildings [2-5]. Some researchers have shown that a closed greenhouse can collect almost three times its own annual heating demand [1, 2, 6-10]. Co-generation and other supplementary system have also been proposed to supply part of the energy demand at peak load [3]. However, a combination of seasonal and short-term thermal energy storage could be an alternative. Although higher amount of solar energy can be harvested in a fully closed greenhouse, in reality a semi-closed greenhouse concept is possibly more practical [5]. Then, a ventilation system is integrated with TES and supplies fresh air as a quick response for the indoor climate control system [4]. This paper presents a comparative study on indoor climate and thermal energy analysis for an ideally closed greenhouse and a closed greenhouse with air infiltration. Heating and cooling loads are assessed together with the need of thermal energy storage for a variety of operating strategies. This study is based on one commercial greenhouse situated outside Stockholm, Sweden.

The Closed Greenhouse Concept with Integrated Thermal Energy Storage

The closed greenhouse concept can be defined according to Armstrong [9]:

"A greenhouse, which is completely closed, no windows to open to release excess humidity or to cool the house when it is too warm".

Today, a large fraction of commercial greenhouse area is heated using oil [11]. A closed greenhouses can in principle be independent of fossil fuel in that they are designed to maximize the use of excess solar energy gained in the summer for winter heating, by integrating seasonal and/or short term TES [3]. Also they can be independent of weather situation therefore and thus be used all over the world. Important design considerations for the concept are: geology of the ground, type of TES and rate of solar irradiation [9]. Although most greenhouses are located in cold climates, it should still be possible to use the concept in a hot and arid region, although in summer the temperature of the storage must be maintained low enough for cooling [12]. Closed greenhouses can be more expensive than open greenhouses as far as first cost, but still they have the potential of becoming cost competitive as compared to open type [4]. Cost competitiveness of closed greenhouses is dependent on size, as well as on the type of TES technology used and other installations. However, no detailed investigation into the effect of design parameters and system layouts on cost-effectiveness is presented in the literature to this date.

One thermal energy storage concept proposed for the closed greenhouse is underground thermal storage systems [13]. For example, an aquifer storage is integrated with a heat pump system for heating and cooling a closed greenhouse (Fig 1).

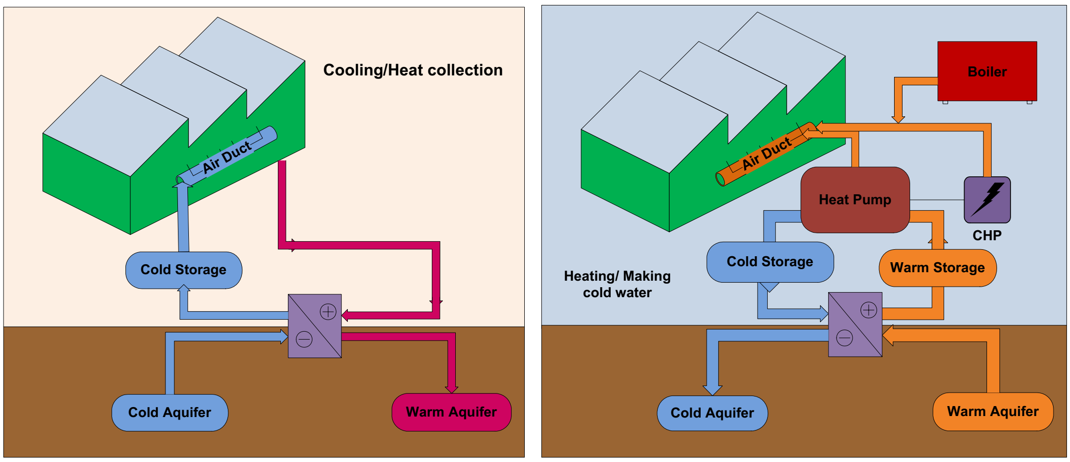

Fig 1. Heating and cooling process in the closed greenhouse (based on [13]).

As shown, in the case where there is not enough heat in the storage system, a boiler can be used to cover the additional required heat [13]. For cooling, cold water from the cold aquifer is pumped into the system and removes heat via a heat exchanger system (Left Hand Side). Then, the warmed water is brought to the warm aquifer for storage. Water at the other side of the heat exchanger is cooled and brought to a short term cold storage. From this storage, cold water provided as needed to the air handling unit and collects the heat from the greenhouse before returning to complete the loop. In the heating process (Right Hand Side) the greenhouse will be heated using a heat pump. Water from the warm aquifer releases its heat in the heat exchanger. On the other side of the heat exchanger, the now warmed water is brought to the heat pump as a low temperature heat source. With electricity input the temperature is raised such that heat can be provided and then supplied to the greenhouse. The system layout can benefit from peak demand-levelling heat storage.

Effective integration of TES is essential, and it can compensate the mismatch between energy supply and demand [14]. It can also improve the reliability and total efficiency of energy systems and thus TES is important for energy conservation [15]. Therefore, TES is the key to any sustainable thermal system in buildings [16]. The basic principle of TES is that energy should be supplied to the storage device when there is excess, and supplied from the storage to a demand whenever it is needed. It is based on the change in internal energy of the material and uses one, or a combination of sensible, latent and chemical reaction heat utilization. [16]. The choice of storage medium is highly dependent on the duration of storage and it should be designed according to its application [17]. The closed greenhouse concept is primarily in need of a seasonal storage; however short term storage may also be required in an optimally designed system. Examples of seasonal TES at reasonable cost are underground borehole storage (BTES), or aquifer storage (ATES) [16]. Aquifer storage is generally preferable if available – they do not exist in all locations. BTES, on the other hand, is possible in most locations but compared to ATES, BTES is associated with slower heat transfer process between the ground and the heat transfer fluid in the boreholes. This leads to low power properties even though the storage capacity of the ground can be large. With BTES, there is definitely a need to integrate solution for peak demand management, like a short-term TES.

Energy analysis and closed greenhouse model

Here, an energy analysis of a closed greenhouse has been carried out using commercial transient simulation software [18]. Mass and energy balances are the governing equations used to model the various processes in a thermal system. To model the greenhouse, the mass and energy balances (for both overall and sub-systems) have been described by many researchers, e.g. [19-23]. They all differ in terms of the assumptions and simplifications considered, and also the level of detail in the modelling scheme. Below, a general description is given for the model and assumptions used in the present study. This model is principally based on the ones previously presented by Hill [19], and it was chosen since evapotranspiration, that is caused by the plant respiration and photosynthesis, has been considered. Thus this model can describe the greenhouse indoor climate more realistically.

To carry out the energy analysis of a closed greenhouse, the overall system is modelled as one control volume with heat transfer, mass transfer and momentum transfer interactions with the surroundings. Variables such as temperature, humidity, pressure and ventilation parameters, describe the system's conditions. The internal source/sink term for variables can be considered in this model as well. Energy and mass conservation equations are used to apply the rate of change of system state. The schematic of energy flow in this model is shown in Fig 2. Here, it can be seen how heat is exchanged between the greenhouse and the surrounding: heat transfer between the greenhouse and the ground, the solar irradiation, the transfer to/from the TES and ambient air are the external fluxes. The transpiration and radiation from plants can be regarded as the internal source terms. A more detailed description on the heat transfer modelling is presented by Hill [19]. Since there is not any standard sub-routine for a greenhouse it was modeled using a multi-zone building project, combined with additional sub-routines to control more parameters linked to the greenhouse indoor climate on the software uses a combination of analytical and empirical equations verified by developers [18]. In the present study, the Ulriksdal greenhouse was used as a case study and model validation. Ulriksdal greenhouse is located in Stockholm, Sweden and consists of public and non-public sections, both of which are considered in the energy analysis. Table 1 presents a summary of the greenhouse characteristics which are used in the model. In order to decrease the level of complexity during modeling, the following assumptions have been made:

- Two scenarios are assumed in terms of infiltration ratio: I) an ideal fully closed greenhouse; and II) a closed greenhouse which has some leakage due to infiltration.
- The infiltration ratio for case II is assumed to be $0.5h^{-1}$ which is constant in non-public due to small leakage through walls [8]. Infiltration ratio in the public zone is defined to be $1.5h^{-1}$ in working hour and $0.5h^{-1}$ for the rest time [8].
- The weather data is based on Meteonorm published by METEOTEST [18].
- The effect of human respiration and heat gain by the personnel is considered to be a constant number of persons in each zone during working hour.

- Artificial light schedule is based on day-night time regardless of solar irradiation.

For assessing possible TES layouts some pre-design calculations on long and short term TES supplement the above energy analysis model.

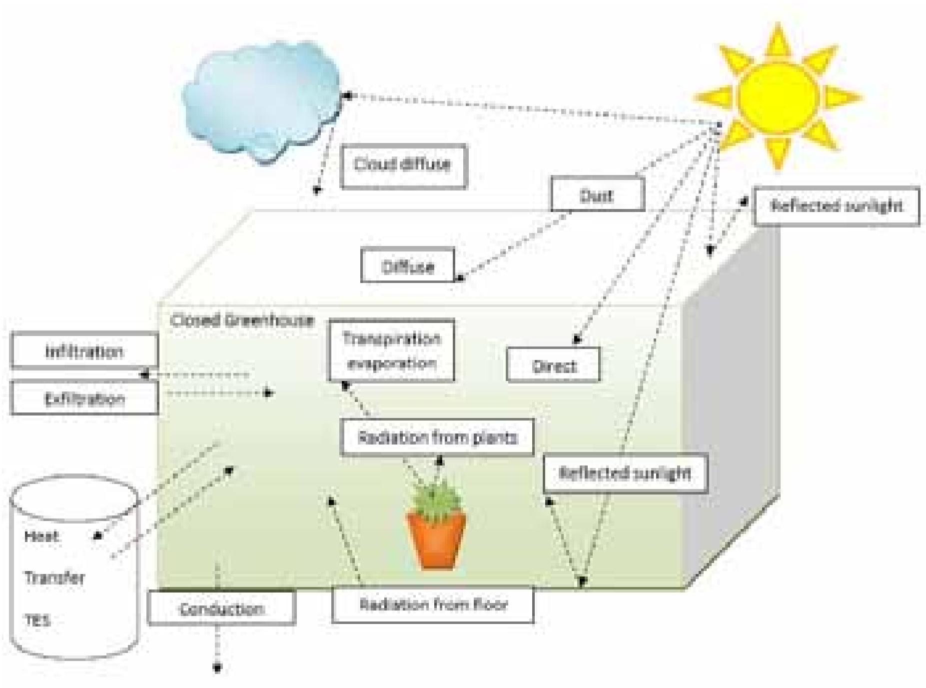

Fig 2. Schematic of energy flows in a closed greenhouse concept

Table 1. Constant parameters that is used in the model.

Parameter	Value	UNIT
Total Area Non-Public Area Public Area	**4600** 2700 1900	**m^2** m^2 m^2
Total Volume	13700	m^3
Set Temperature	18-20	^{o}C
Upper limit of RH (Dehumidification)	85	%
Lower limit of RH (Humidification)	75	%
Time base	1	hour

Results and Discussion

Based on the modeling of the closed greenhouse, the heating and cooling load is calculated to give hourly and monthly values. The cooling load is the same as the summer excess heat; therefore this amount of excess heat should be removed and stored in a seasonal TES for later use. From the modeled case of Ulriksdal, Sweden, the cooling and heating demand of an ideal closed greenhouse is presented in Figure 3. Here, the monthly cooling/heating load (MWh) is shown. One parameter to consider is the ratio between cooling and heating demand which is here denoted Excess Energy Ratio (EER). Thus, the EER expresses the ratio between available excess thermal energy that can be stored in the TES system and the annual heating demand of the greenhouse. From the monthly analysis it can be concluded that the EER is about three in the ideal fully closed greenhouse. The heating and cooling demand is compared with and without considering the infiltration through the closed greenhouse and the results are presented in figures 4 and 5.

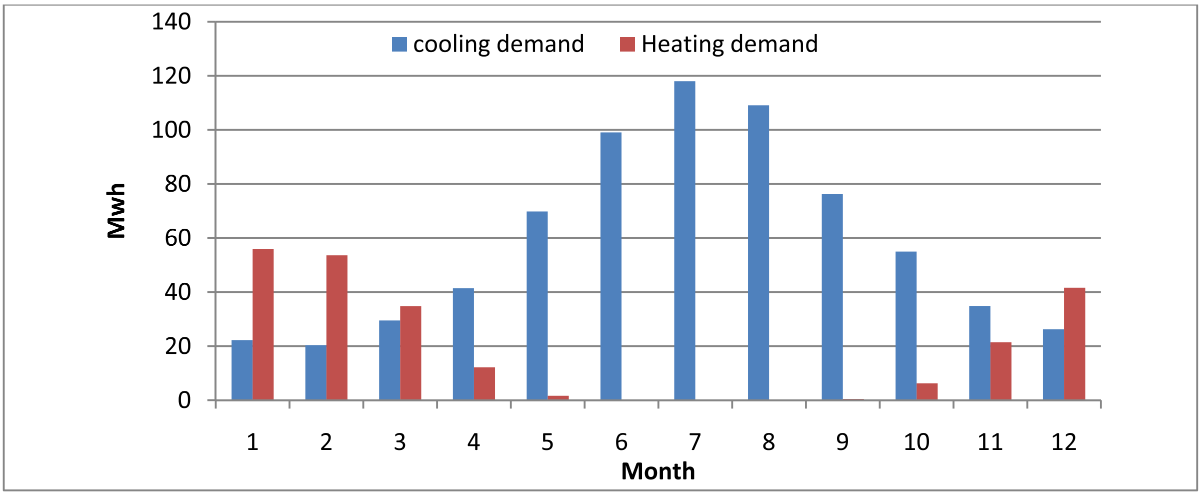

Fig 3. Thermal energy demand in the ideal closed greenhouse

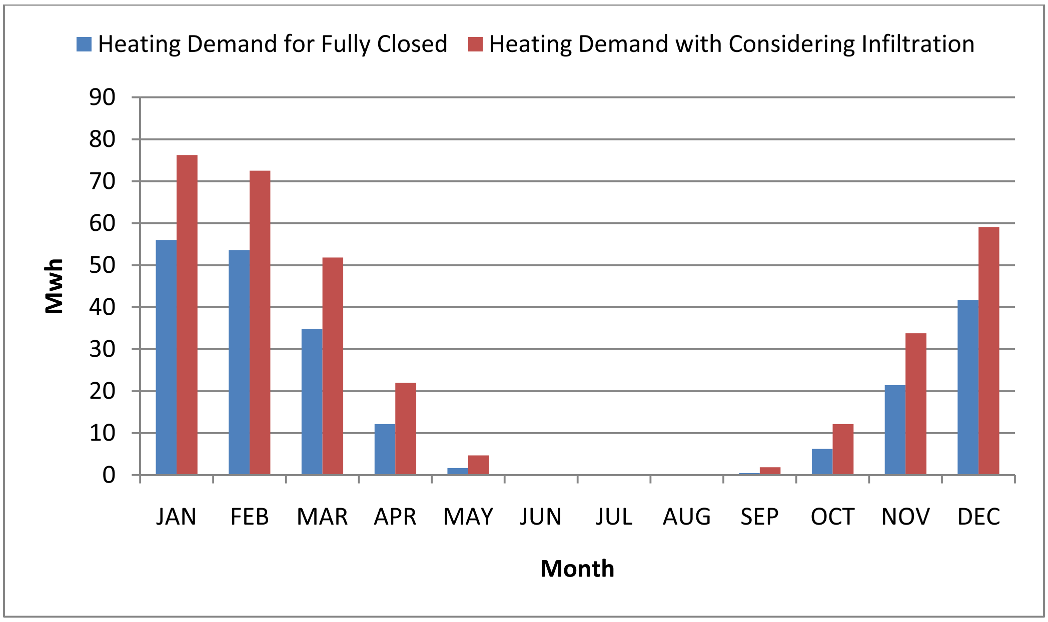

Fig 4. Comparison of heating demand with and without considering leakage through closed greenhouse

Here, the annual heating demand difference between these two cases is about 110 MWh, while the annual cooling demand difference is 60 MWh. This leads to a 32% increase and 9% decrease in heating and cooling demand, respectively, as compared to the ideal closed greenhouse. Furthermore, it should be noted that the EER is reduced to 2 when considering an infiltration rate of about 0.5 h^{-1} through the greenhouse structure.

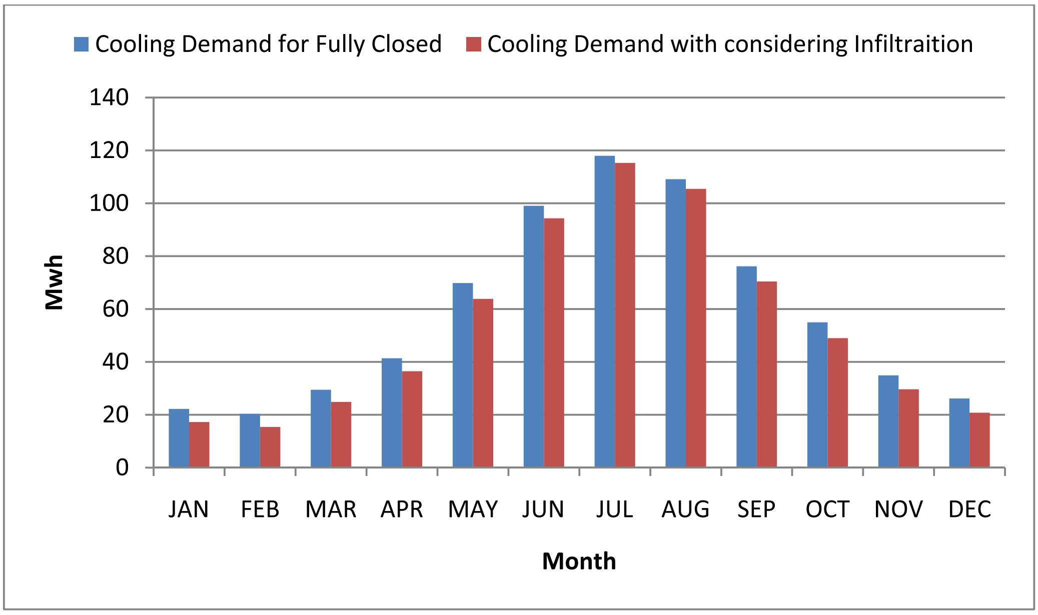

Fig 5. Comparison of cooling demand with and without considering leakage through closed greenhouse

Ulriksdal greenhouse presently uses oil as the energy source for the boiler in order to supply heating demand of the whole greenhouse. The energy content of EO1 is around 9950kWh/m^3 [24]. The oil consumption is around 200 m^3 per year, corresponding to 1.6 GWh annual heating consumption if a 75% boiler efficiency is considered. This means an annual energy demand of 320 kWh/m^2 while the heating demand in an ideally fully closed greenhouse obtained from the developed model is about 50 kWh/m^2. This significant difference in heating demand in closed and open greenhouse is presumably due to a considerable infiltration in the actual greenhouse. It is likely that cases where the ventilation window is opened to control humidity occur at the same time as heat is provided to control the temperature.

In order to store and utilize the excess thermal energy through the closed greenhouse, a TES system must be designed. This can be done based on peak and/or base load thermal energy demand which leads to the design of long term and short term storage system, respectively. Table 2 shows the maximum hourly average and maximum monthly average thermal energy demands obtained in the model, and these are here used to represent the peak and base loads, respectively. Table 3 presents the number of boreholes required for the seasonal thermal storage if peak and base loads are considered for design. For the case where only seasonal storage has been considered to supply thermal energy for an ideal closed greenhouse the peak load is the design load. Then, when considering an achievable borehole power of 40 W/m and a capital cost of 27.5 Euro/m for a single borehole [25], the total investment cost for the BTES system becomes 472500 Euro per hectare closed greenhouse. With an oil consumption equivalent to the case of Ulriksdal the annual cost of oil is about 256000 [26] Euro per hectare, such that the payback of the borehole investment would only be 2 years. It is of course essential to consider the cost of the extended technical system (air handling units, heat pumps, etc) for the full cost effectiveness analysis, as well as the profit from the presumed gain in production yield ratio and saved water consumption which is obtainable in a closed greenhouse. Short term TES can be used as an alternative in order to supply energy peak demand. One previous study has shown that a combination of short term and long term thermal storage can reduce the total capital investment for TES system by up to 40% [25] PCM thermal storage system can be one candidate for the short term storage system. A water tank can also be considered for peak shaving if there is not any space limitation in the system since it needs about four times the space rather than a PCM storage. However, the cost of water storage may be four times less than for PCM storage [25].

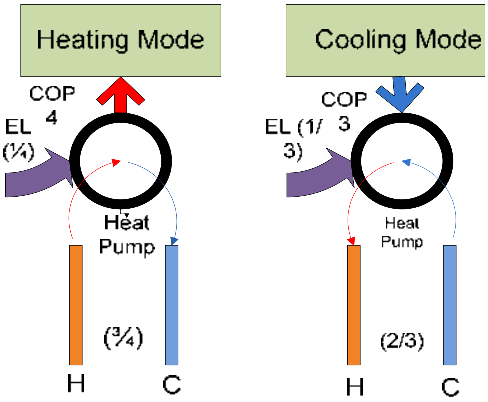

Fig 6. Energy flow for heating and cooling process in the BTES

Table 2. Maximum Heating and cooling demand per hectare of greenhouse

Max Heating demand _Hourly based:	450	KW/hectare
Max Heating demand _Monthly based:	170	KW/hectare
Max Cooling demand _Hourly based:	630	KW/hectare
Max Cooling demand _Monthly based:	360	KW/hectare

Table 3. Borehole sizing based on hourly and monthly maximum thermal demand

	Based on peak heating demand	***Based on base heating demand***	***Based peak cooling demand***	***Based on base cooling demand***	***Depth of borehole***	***power of borehole***
Number of borehole	*76*	*28*	*105*	*60*	*150 m*	*6 kW*
Number of borehole	*46*	*17*	*63*	*36*	*250 m*	*10 kW*

Concluding remarks

Preliminary results based on the theoretical modelling of a closed greenhouse indicate that the ideal closed greenhouse concept can significantly reduce the annual auxiliary energy demand. The surplus of available energy in the ideal closed greenhouse is close to three times more than its total heat demand; although in reality it becomes less due to infiltration. Thus, the further effect of varying infiltration ratio on the excess energy ratio can be studied in future research.
Based on the case study of fuel cost analysis, it can be concluded that the closed greenhouse integrated with short term and seasonal TES has a large potential of becoming cost effective, with the cost analysis herein showing that the investment for the seasonal storage only could be paid within about two years due to the savings in auxiliary fuel. In continuing studies of this concept, the type and size of thermal energy storage should be optimized in order to achieve the highest available efficiency and cost effectiveness.

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