Building façade integrated solar thermal collectors for water heating: simulation model and case studies

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Abstract: This paper presents a dynamic simulation model for the energy, economic and environmental performance assessment of a novel building integrated solar thermal collector prototype, for Sanitary Hot Water (SHW) preparation. The investigated device is a Flat-Plate Collector (FPC) with water as working fluid, suitably designed to be integrated into the building envelope (Building Integrated Solar Thermal System - BISTS). The developed model was conceived for assessing the active effect of the collector as well as the influence of its building integration on the building thermal loads (passive effects: overheating and free heating). The main differences of the proposed novel collector vs. the existing technologies consist in a higher system simplicity and in low fabrication costs. In order to show the features of the developed simulation model, a comprehensive case study was developed. In particular, the proposed system layout (PS) refers to the installation of the examined FPC prototype on south facing façades of a residential building located in different climate zones and with different envelope's weighs. A reference system layout (RS) is also taken into account for comparison purposes vs. the proposed one in terms of energy, economic and environmental performances.

Keywords
Building integrated solar thermal systems, energy performance analysis, experimental validation

1. Introduction

Nowadays the building sector is responsible about of 40% of the total primary energy consumption and for 30% of greenhouse gas emissions in OECD Countries (IEA 2015). These results are mainly due to the building HVAC and SHW preparation systems. The solar based renewable technologies are, among the available ones, the most promising in term of energy saving and carbon emission reduction for building applications (COST Action 2015). Building Integrated Solar Thermal Systems (BISTS) represent, in fact, a successful way to profitably use a renewable energy also approaching the energy efficiency goals by boosting the sharing of renewables (IEA 2015). However, BISTS are still far from a massive diffusion due to several technological and economic implications (Energy et al. 2014). One of the main novelties of the analysed FPC prototype is represented by its simplicity and low fabrication cost, which returns a higher economic convenience in its implementation if compared to commercial ones. Besides the active effects (SHW preparation and HVAC systems support), it is worth noticing that the BISTS substantially affects the building thermal loads (passive effects). The BISTS adoption could lead to a free heating effect during the winter as well as to a superheating effect during the summer due to the temperature reached by the building integrated collectors. Regarding this phenomena very few studies are available in literature and in particular on building integrated Flat-Plate Collector (FPC) with water as working fluid (Lamnatou et al. 2015). In this paper a new dynamic simulation model developed and validated for this technology is presented. The model was implemented in a computer code written in MatLab. In order to show the potentiality of this tool a novel case study referred to a residential building located in different weather zones was developed.

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2. Code Description

The presented code is able to simulate the energy performance of the solar thermal collector as well as the building thermophysical behaviour. The model developed for the energy performance analysis of the solar collector was experimentally validated whereas for the building energy performance assessment the standard procedure related to the EN 13790 was taken into account. A subsequent merge of such models was made in order to get a complete simulation tool for whole building energy demand analysis (integrating the solar collectors). In the following a short description of the model is carried out.

2.1. Solar thermal collector

The considered water collector prototype (Fig. 1, left), consists of: i) a single layer glass; ii) a header and risers copper pipe line; iii) a selective surface (TiNox) absorber plate; iv) an insulation layer (glass wool); v) a galvanised metal sheet case. The main geometrical features of the collector are reported in Table 1.

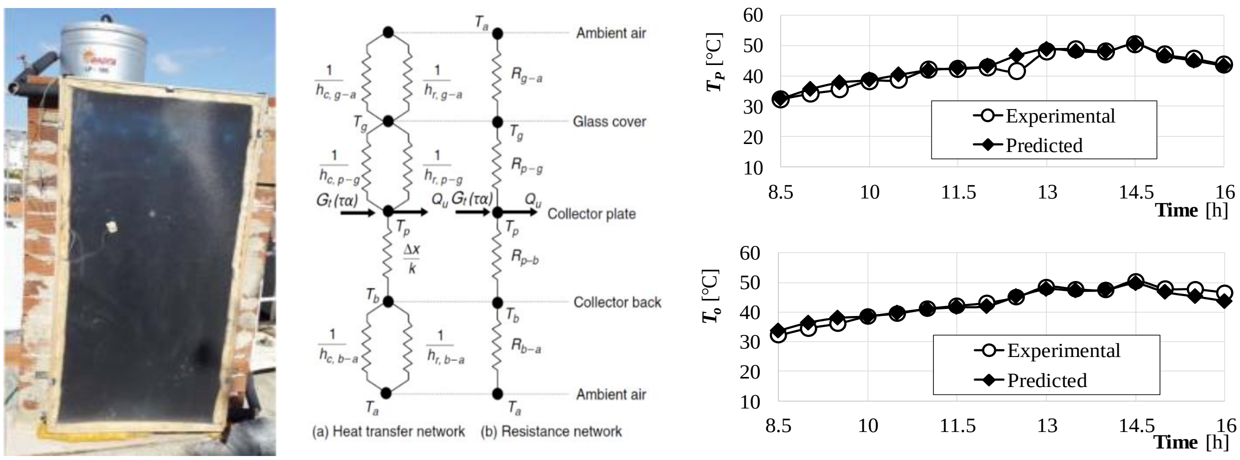

Fig. 1. FPC prototype, model thermal network and simulation/experimental results

Table 1. FPC design parameters

Collector length [mm]	1600	Glass transmittance [-]	0.93
Collector width [mm]	900	Insulation conductivity [W/m K]	0.041
Insulation thickness [mm]	25	Absorber plate absorbance [-]	0.95
Pipe diameter [mm]	22 (header), 8 (risers)	Absorber plate emissivity [-]	0.04
Pipe thickness [mm]	1	Number of risers [-]	7

The developed collector is expected to have an initial cost remarkably lower than the ones of the present commercial collectors. Such peculiarity could boost the diffusion of the presented collector for building integrated applications. For the its energy performance analysis a suitable simulation model has been developed. The dynamic simulation model was obtained by those proposed in (Duffie and Beckman 2013, Kalogirou 2014). Basically, the model is represented by thermal network reported in Fig. 1 (middle). The main assumptions considered in model energy balances are: thermodynamic equilibrium, steady state regime, one dimensional heat transfer, negligible kinetic and gravitational terms. The general formulation for the calculation of the solar thermal collector's efficiency can be obtained from the Hottel-Whillier equations set based on the assessment of energy losses and useful energy. The latter, under steady-state conditions, is equal to the rate of energy absorbed by the working fluid minus the occurring heat losses:

$$Q_u = A_C \left[G_t \left(\tau\alpha \right) - U_L \left(T_p - T_a \right) \right] = \dot{m} c_p \left(T_o - T_i \right) \qquad \text{Eq. (1)}$$

where: G_t is the incident total solar radiation, [W/m^2]; $\tau\alpha$ is the product of the solar transmittance of the glass cover and the absorbance of the absorber plate; $\dot{m}$ is the working fluid mass flow rate, [kg/s]; T_o, T_i and T_p are the water outlet, inlet and plate temperatures, respectively, [K]. The plate temperature is a system key parameter in terms of building thermal behaviour. It can be assessed as follow:

$$T_P = T_I \times Q_U / \left(A_C F_R U_L \right) \times \left(1 - F_R \right) \qquad \text{Eq. (2)}$$

where: U_L represents the overall heat losses coefficient, [W/K] and F_R is the heat removal factor, [-] (indicating the ratio of the actual useful energy gain that would result if the collector-absorbing surface had been at the local fluid temperature).
The code was experimentally validated through performance test data. Note that the developed model is conceived for a thermosiphonic behaviour of the collector. The calculation of the water flow rate was carried out by using an experimental equation (Koffi et al. 2008):

$$\left(1 + \varphi \right) \times 128 \nu L_{cl} \dot{m} / \pi N d^4 \text{ - } g \rho \beta' \sin\theta \frac{L_{cl}}{2} \left(T_{fo} - T_{fi} \right) = 0 \qquad \text{Eq. (3)}$$

where: φ characterizes the resistance to the water flow in the collector and connection tubes, [-]; ν is the kinematic viscosity, [m^2/s]; L_{cl} is the collector height, [m]; N is the number of risers; d is the internal diameter of the risers, [m]; ρ is the water density, [Kg/m^3]; θ is the collector slope, [°]; T_{fo} and T_{fi} are the outlet and inlet water temperatures, [°C]. A very good agreement between the simulated outlet water and plate temperatures and the correspondent experimental data is achieved (Fig. 1, right).

2.2. <u>Heating and cooling demand</u>

The algorithm adopted for assessing the building heating and cooling demand is the hourly method proposed by (ISO13790 2008). For simulating the building envelope thermal behaviour such algorithm refers to five resistances and one capacitance (5R1C) thermal network (Fig. 2, left) The related solving model is based on a Crank-Nicholson scheme, considering a time step of 1 hour. For each time step the internal air temperature (θ_{air}) is calculated by:

$$\theta_{air} = (H_{tr} \times \theta_s + H_{ve} \times \theta_{\sup} + \phi_{ia} + \phi_{HC,nd}) / (H_{tr} + H_{ve}) \qquad \text{Eq. (4)}$$

where: H_{tr} and H_{ve} are the internal surfaces to air and ventilation conductances, respectively, [W/K]; θ_s and θ_{sup} are the wall internal surface and external air temperatures, respectively, [°C]; ϕ_{ia} and $\phi_{HC,nd}$ are the internal heat loads and the power supplied by the HVAC system, respectively, [W]. With the aim to assess both the active and passive effects, the ISO13790 simulation model was suitably linked to the above mentioned solar collector model. This target is obtained by means of the modified thermal network reported in the Annex B of ISO 13790 and originally developed to simulate a multi-zone building (Fig. 2, right). Here, the boundary condition related to the solar collector is taken into account through a suitable virtual space adjacent to the thermal zone under investigation. The surface node s is connected to the equivalent temperature θ_{es} that is averagely weighted on walls areas and transmittances. By such assumption, the code is able to assess the BISTS passive effects by simply substituting the temperature of the above mentioned adjacent space with the one of the collector absorbing plate (by suitably changing the wall transmittance). Additional model modifications have been taken into account in the code in order to better assess the solar gains thought the windows, usually overrated by the 13790 algorithm (P Narowski 2009, Oliveti et al. 2011, Michalak 2014, Bruno et al. 2015, Bruno et al. 2016).

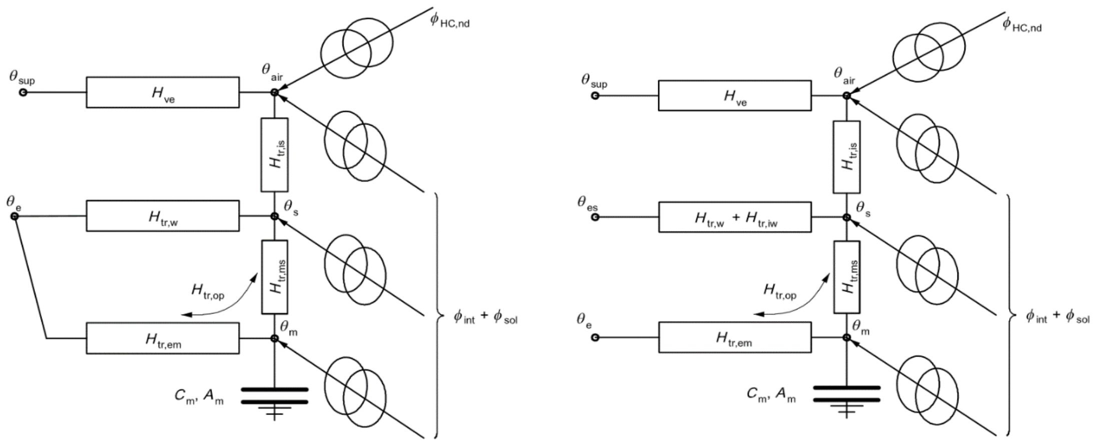

Fig. 2. ISO 13790: simulation model thermal networks

3. Case study

The case study has been developed with the aim to show both the Proposed System (PS) active and passive effects. Specifically, a single room (52.8 m^2, Fig. 3), included in a dwelling multi-floor building located in different European weather zones (Table 2), is considered. The related climatic conditions are accounted through Meteonorm hourly files. For these locations, in this table the main climate indexes and the considered HVAC system scheduling are also reported. Three different building envelope weights were taken into account (light: 150 kg/m^2, medium: 250 kg/m^2, heavy: 500 kg/m^2). Heat transfer is taken into account through a South facing wall (23.76 m^2) and window (4 m^2). A brick wall (U = 1 W/m^{2}K) and a double glazing window (air, 4-6-4, U = 4 W/m^{2}K, SHGC = 0.78) is modelled.

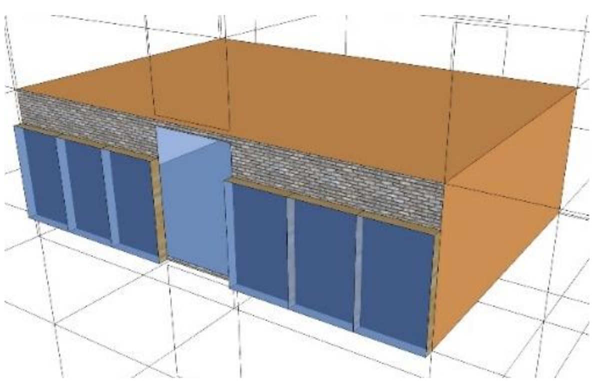

Fig. 3. Sketch of the modelled building space

Table 2. Weather zones, heating/cooling periods

Weather zone	HDD [Kd]	Heating period (schedule)		Cooling period (schedule)
Copenhagen	3757	15/10-30/4	(24/7)	1/6-30/9 (10-18)
Prague	3734			
Brussels	3221			
Dublin	3210			
Freiburg	2699			
London	2870			
Milan	2584	15/10-15/4	(8-11, 13-24)	
Nice	1506	1/11-15/4	(8-10, 13-23)	
Rome	1370			
Naples	1335	15/11-31/3	(8-10, 14-22)	
Athens	1082	1/1231/3	(8-10, 15-21)	

All the other building surfaces are considered as adiabatic. Six building integrated FPCs (2.4 m^2 each) were modelled on the South façade. For comparison purposes a Reference System (RS) is also modelled. During the cooling period, a window shading device (internal, SHGC = 0.3) was taken into account with the aim to reduce the solar gains. A gas fired heater (efficiency: 0.9) for the SHW preparation and an electric heat pump/chiller for space heating and cooling (heating COP: 3.5; cooling COP: 3) are taken into account. Heating and cooling set-points of 20 and 26°C are considered, respectively. The SHW demand is set equal to 350 litres per day. Internal thermal loads of 4.2 W/m^2 and air infiltration of 0.5 Vol/h are taken into account. An electricity and natural gas cost of 0.21 €/kWh and 0.80 €/Nm^3 are taken into account in the economic analysis.

4. **Results and discussion**

The performed analysis shows interesting energy, economic and environmental results. The passive and active effects behave in different way on the building total energy needs and thus they must be separately dealt with.

Passive effect

An interesting aspect of BISTSs is their influence on the building thermal behaviour while producing the active effect. The HVAC system energy needs variation, induced by the BISTSs installation, could be helpful or disadvantageous (as a function of the occurring season, technology, envelope typology and weather zone). The system proposed in this case study affects the space thermal behaviour through the south wall where the integrated solar collector: i) in daytimes increases the building heat gains (the wall internal surface temperatures are higher than the ones detected in traditional buildings); ii) in night times potentially increases the building heat losses (the wall temperatures are lower than the ones of traditional buildings because of the long wave radiative loss to the sky). Note that the ISO EN 13790 approach takes into account only one thermal node for all of the internal surfaces. Therefore, the temperature increase of the south facing wall is lumped on all the other opaque elements. In Fig. 4, for the medium weight building located in Naples the internal wall temperature differences in case of BISTS and No BISTS are reported for a sample winter (left) and summer (right) day. By this figure it can be observed that, the absorber plate temperature is always higher than the corresponding SolAir one (a resulting increase of the internal wall temperature is obtained).

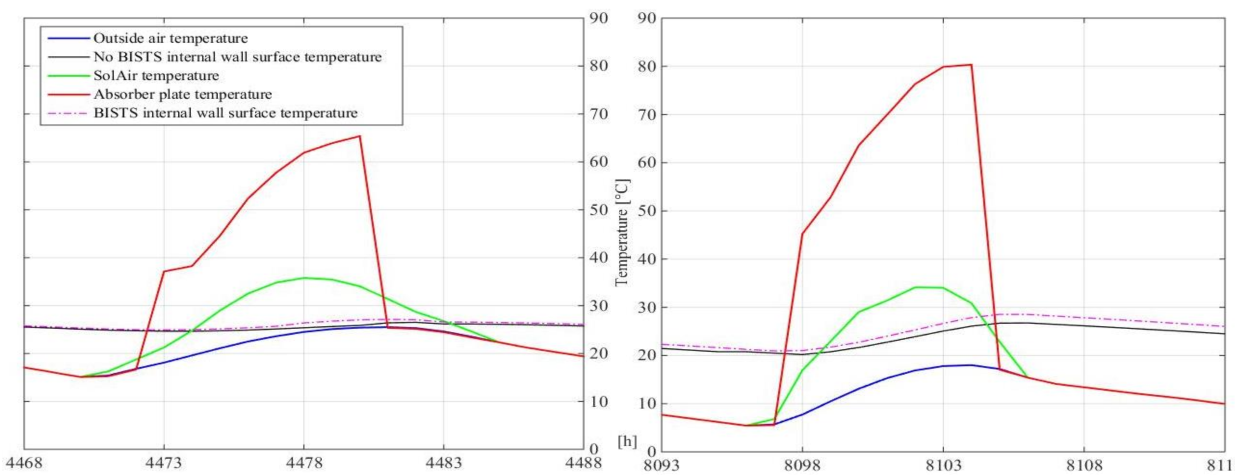

Fig. 4. Winter and summer time histories of the simulated building temperatures

For such reason, the BISTS returns a free heating effect in winter and a superheating effect in summer. Note that, for the assumptions considered in this case study no higher night heat losses are detected in case of BISTS adoption. The overall passive effects on the yearly building energy demand strongly depends on the length of the cooling and heating seasons. Obviously, the simulation results show better energy performances in heating dominated weather zones. In Fig. 5 the yearly variations of the primary energy demand required by the HVAC system between traditional and BISTS adoption buildings are reported for all the considered building weights. As it is possible to observe, for the investigated heating dominated weather zones through the BISTS adoption an energy saving is always achieved. Better results are obtained for heavyweight buildings (the higher the extra heat stored into the envelope during the sun hours the higher the heating energy saving). Conversely, for the climate zones of Athens and Naples an increase of primary energy demand due to the BISTS passive effects is detected. In Milan, the BISTS convenience depends on the envelope thermal inertia.

Active effect

In this paper the BISTS active effect regards the energy saving obtained for the DHW production. In Table 3 the related primary energy needs for reference and BISTS buildings (RS and PS, respectively) are reported. Large energy saving amounts are detected, the highest one are obtained in hot summer climate zones, as expected.

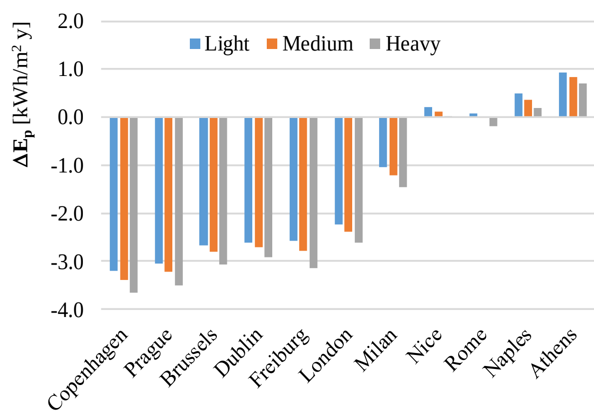

Fig. 5. HVAC system primary energy saving

Table 3. SHW system primary energy saving

Weather zone	RS	PS	Δ	
	kWh/m²y			%
Copenhagen	93.6	44.3	-49.4	-52.7
Prague		47	-46.6	-49.8
Brussels		46.8	-46.9	-50
Dublin		45.5	-48.1	-51.4
Freiburg		39.4	-54.2	-57.9
London		46.9	-46.7	-49.9
Milan		33.6	-60.0	-64.1
Nice		17.7	76.0	-81.1
Rome		15.7	-77.0	-83.3
Napoli		19	-74.0	-79.7
Athens		16	-77.6	-82.9

Overall effect

By the above presented results, it is possible to observe that BISTS buildings return higher energy savings for their active effect rather than for the passive one. In Fig. 6 the overall yearly primary energy savings for all the simulated conditions are reported. In this figure it is clearly visible that the BISTS system layout always returns a remarkable energy saving vs. traditional buildings also in weather zones where increased HVAC system energy demands are detected. In particular, results show higher conveniences for heavyweight building envelopes. The overall yearly economic savings and avoided CO_2 emissions are reported in Fig. *7*. Here, it is possible to observe that low economic savings and remarkable avoided CO_2 emissions (up to 900 Kg_{CO_2}/y) are obtained.

5. Conclusions

In this paper a novel dynamic simulation model for the energy performance analysis of a building integrated solar thermal collector was developed and experimentally validated. The model was embedded in the ISO 13790 standard procedure for the whole heating and cooling analysis (in addition to the DHW production assessment). The resulting complete model was implemented in a computer tool written in MatLab. By such code both active and passive effects due to the integrated solar collectors are taken into account. In order to show the potentiality of the presented code a suitable case study related to a residential building located in several weather zones is presented. Here, different building envelope thermal inertia are investigated with the aim to find out the optimal design solution. By the carried out analysis interesting results are obtained. In particular, remarkable energy saving are achieved mostly regarding the SHW production. Significant outcomes are also obtained through the passive effect analysis. In particular the free heating effect allows a remarkable reduction of heating loads and demands in cold winter climate zones. Conversely, for the hot summer areas, relevant superheating effect are observed (in these cases standard stand-alone layout can be preferred to the vertical building integration by also selecting the optimal collectors slope). In any cases by also accounting the SHW production through the investigated façade integration layout remarkable energy savings and avoided CO_2 emissions are achieved vs. traditional buildings. Obviously, the best overall performances are obtained where the annual incident solar radiation is high. For Nice, Rome, Naples and Athens the primary energy savings and the avoided CO_2 emissions calculated in the developed case study surpass 45% and 800 kg/y.

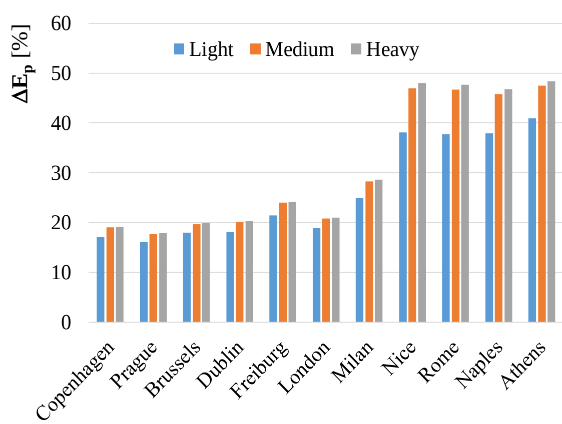

Fig. 6. Overall primary energy savings of BISTS layouts

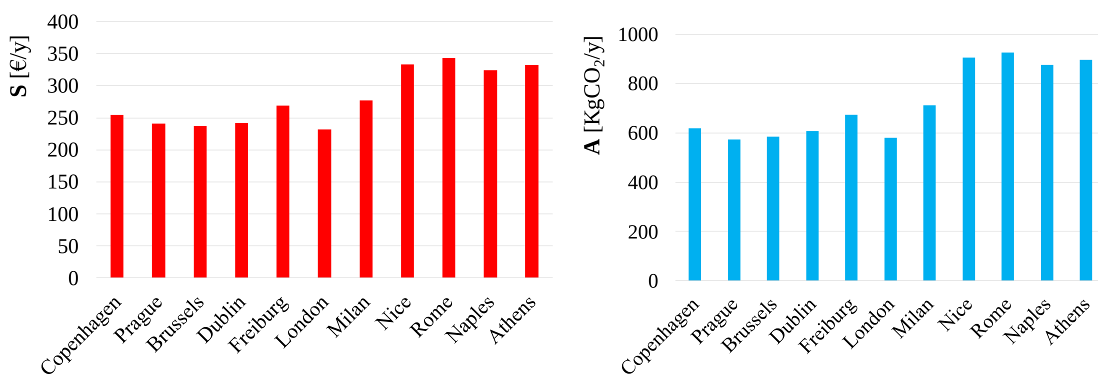

Fig. 7. Yearly overall economic saving and avoided CO_2 emissions

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