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Solar heat generation in Estonia and its peculiarities

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Abstract

Solar energy-based heating technology in Estonia has passed its early phase of development and moved into commercialization. In this paper an attempt has been made, by way of computer simulation, to analyse the justification of the usage of evacuated tubular collectors, which have become popular there. Their average seasonal efficiency is 9% higher than a flat plate collector with an equal absorber area. Due to peculiarities of the Estonian (radiation) climate, some techniques are recommended with which to improve energy yield.

Keywords: evacuated tubular collector, computer simulation, flat plate collector

1. Introduction

This paper's aim is two-fold: to demonstrate how solar-thermal technology has developed in Estonia and to establish the suitability of today's spontaneously-developed systems.

The peculiarities of technological development in any location depend mostly on geographical and economical preconditions. Estonia is located in the north-east of Europe between latitudes of 58 – 59.5 N, with a total area of 45227 km^2 and a coastline length of 3793 km. Its population is 1.34 million and its GDP €10,275 per capita (2009). The average temperature in January is – 4.6 °C and in July, +18.9 °C. Due to its rather cold (and dark in winter) climate, 40.6% of fuel and 25.3% of electricity is used in domestic households [1]. The proportion of energy used to heat domestic water supplies is unknown. Estonia's solar radiation regime is influenced by its high latitude and location in the path of Atlantic cyclones which cause high levels of cloudiness and alternating weather patterns.

Table 1. Radiation conditions.

	Jan.	azimuth	**July**	azimuth	**Average Per year**
Energy yield, kWh/m^2	13.0		162.6		998
Sunrise (@ Tallinn)	8:34	–52.45°	3:03	–135°	
Sunset (@ Tallinn)	15:26	52.45°	20:57	135°	
Duration of daylight, h (@ Tallinn)	6.6		17.9		

The quality of solar energy is characterized in table 1, which is a summary of [2] and based on actinometrical measurements during the period 1955–2000 (2005). The capital, Tallinn, experiences around 112 days per year without (direct) sunshine. The mean total cloudiness is 7.1 tenths, the mean minimum cloudiness 5.1 tenths. The sector of the sun's azimuth is ~105° in wintertime and 270° in summer. The effective sector of performance for any solar collector, oriented due south, is ~120°, meaning that a lot of energy cannot be transformed and the technologically-available energy resource is significantly lower than actinometrical levels (998 kWh/year). Therefore the effective usage of solar energy requires additional efforts, which are proposed below.

The history of solar-thermal energy conversion in Estonia has three distinct periods:

1. Pre-1990s – DHW systems created by amateur enthusiasts (Fig. 1a).
2. 1990 – 2000 – DHW systems created by humanitarian aid (Fig. 1b).
3. Post-2000s – period of commercialization (Fig. 1c).

a) Home-made DHW system in Tartu.

b) Hospital in Vändra village, a humanitarian aid project.

c) Solar heat co-operative in Tallinn, 600kW.

Fig. 1. Development of solar-thermal conversion technology in Estonia.

Due to the presence of cheap local fossil fuel (oil-shale), research into solar energy conversion (and its applied technologies) did not have any governmental support until recently (2010s). Solar-thermal technologies have therefore developed spontaneously. The simulation below is designed to analyse the suitability of the current popular approaches. Many new domestic hot water (DHW) systems use Chinese-made evacuated tubular collectors (ETCs), instead of traditional flat-plate collectors (FPCs) and it is thus of interest to examine how this use is justified regarding local conditions.

Table 2. Control sites.

Site (abbreviation)	Characteristics (description, population, climate)	Latitude (Lat)	Longitude (Long)	Comments
Tallinn (TLL)	The capital, ~400,000 marine climate	59.48 °N	24.65 °E	
Tartu (TRT)	The second big city, ~100,000, "continental" climate	58.25 °N	26.5 °E	= Tartu-Tõravere Observatory (TO) near Tartu
Pärnu (PRN)	Coastal resort, ~45,000, marine climate	58.38 °N	24.5 °E	

This problem is analysed using the self-created (EXCEL) simulation model for three characteristic locations in Estonia (table 2).

2. Simulation model

Most recently-installed solar collectors are either the FPC from Sonnencraft, model SK-500, or the ETC from Jiangsu Sunpower Solar Technology, SPA-58-1800. Their respective productivities per equal absorber area (1 m^2) are compared, with the following limitations and simplifications:

- The performance period runs from February to October, since during winter months (November, December and January) there is no convertible solar radiation available.
- A storage tank volume of 300 L is modelled, with three layers of stratification, operating sequentially.
- Forced circulation, recommended in the documentation for each collector, braked while losses are over the heat generation.
- An impulse model analyses an evening consumption of 100 L.
- A constant waterworks input temperature of +7 °C.
- Average radiation data collected from TO on the 15th day of each month [2] are used, corrected for TLL and PRN (a difference of a few %). We consider the longitude of PRN = longitude of TLL and the latitude of PRN = latitude of TRT).
- Mean temperatures on the 15th day of each month at each site are used [3].
- An isotropic model of the diffuse fraction G_d is used.
- The input temperature of any higher layer corresponds to the final temperature of the lower layer. The final temperature of the third layer is used to assess unit productivity. We imagine that the daily amount of water passes each layer of stratification per day.
- Losses from the heat-exchanger are not considered.
- The transparency-absorbance product is approximated with the step function $\tau\alpha=1$ if the attack angle (of direct radiation) is $\Theta<65°$, with $\tau\alpha=0$ being used elsewhere.
- Collectors are modelled looking south with a tilt angle of $\beta=45°$.

A flow diagram of the simulation procedure for the first two layers is shown in Fig. 2. Layer 3 corresponds with layer 2 and is not shown. For each hour of operation in the sector of the attack angle $\Theta\in\{130°\}$, the rise in temperature of the heat carrier (water), ΔT_i, is calculated based on the attack angle Θ. For these calculations, equations taken from [4] are used.

The rise in temperature calculation, ΔT_i, °K h^{-1} in Fig. 2, consists of a double-matrix (table 3) which has (for every month) two rows. Here E_h represents the converted primary energy per hour, T_i. the temperature at the end of each corresponding hour and $\Delta T_i= E_h/(\sigma\cdot m_w)$ the temperature increase during the said hour, where σ is specific heat and m_w the flow rate of the heat carrier (water). The temperature increase is added to the starting temperature T_{start}, which then becomes the “start” temperature for the next hour and so on. For the first layer and morning, $T_{start}=+7$ °C. For other layers T_{start} is the output temperature in the lower layer and previous evening.

Table 3. Double-row in the computation matrix.

$h-1$	h	$h+1$	$h+2$
	$E_h=G_T\cdot(\eta_0-U_L(T_{i-1}-T_a)/G_T)$	$E_{h+1}=G_T\cdot(\eta_0-U_L(T_i-T_a)/G_T)$	
T_{start}	$T_i=T_{i-1}+\Delta T_i$	$T_{i+1}=T_i+\Delta T_{i+1}$	

Other symbols have the following meaning:

G_T is global irradiance on the tilted surface, calculated via the equation $G_T = G_{bT} + G_{dT}$; $G_{dT} = 0.75G_d$. Direct radiation, $G_{bT}=f(\Theta)$, is a complicated function dependent on the data table, location, day number and hour. Diffuse radiation G_{dT} is considered in decreased volume as the tilted surface cuts off a quarter of space.

η_0 is the initial efficiency of the collector. For an ETC, initial efficiency increases by 16% compared to documentation data, considering that their efficiency is higher at larger attack angles ($0<\Theta<60°$) [5].

U_L is the overall collector heat loss coefficient, while T_a is ambient temperature.

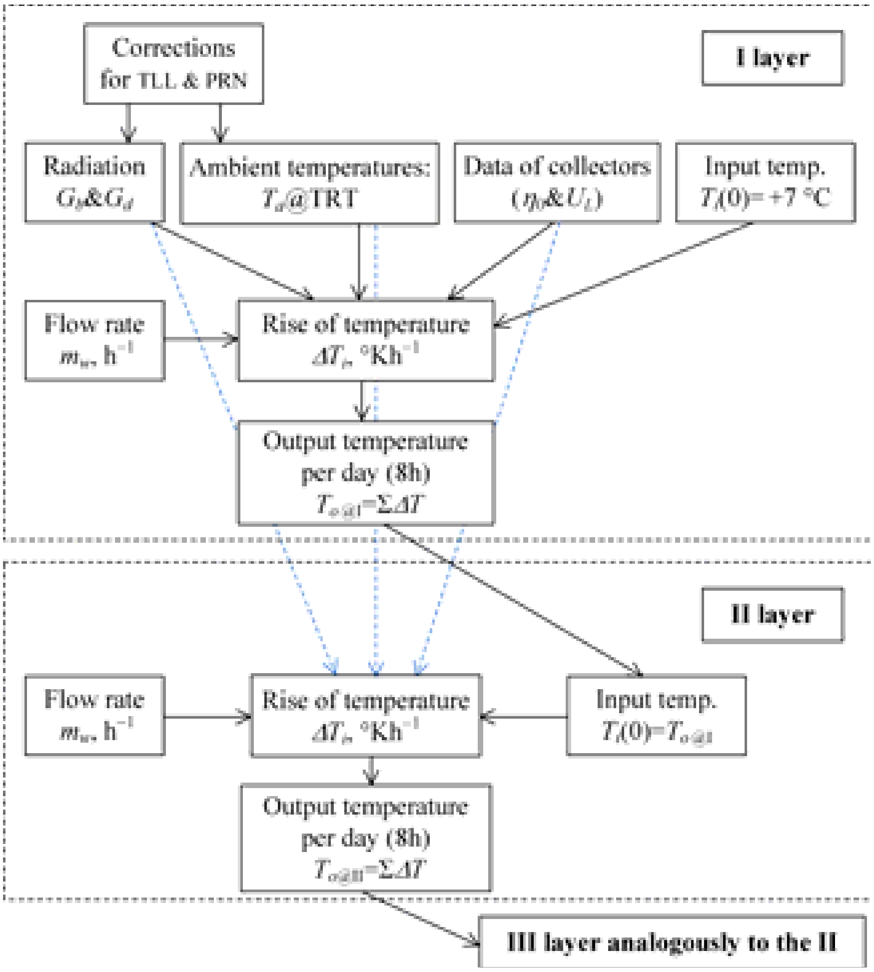

Fig. 2. Flow diagram of the simulation procedure.

The collectors being compared have the following efficiency curves:

SK 500: $\eta=0.795-3.63\cdot(T_a-T_i)/G_T$ and

SPA-58-1800-18: $\eta=1.16\cdot0.67-2.45\cdot(T_a-T_i)/G_T=0.77-2.45\cdot(T_a-T_i)/G_T$

The average efficiency of energy conversion, $\eta_{\text{average}}=\Sigma E_h/\Sigma G_T$, can be defined as the sum of the converted energy divided by the sum of radiation (for the corresponding time interval: per day, month etc.).

3. Simulation Results

The results of the simulation are presented in the following graphs. Fig. 3 shows the relationship between average daily efficiency and month at each site. The difference between sites is practically negligible. The ETC always has a higher efficiency than the FPC, with a greater difference during cold months. Maximum efficiency (in August) does not coincide with maximum radiation (June), due to the higher ambient temperature during August. Fig. 4 shows the time interval during which (in terms of the simulation model) no additional heating is required to achieve evening output temperatures of over 50 °C. It is apparent that for the ETC, this interval is nearly a month longer and starts earlier, although the difference is reduced in autumn.

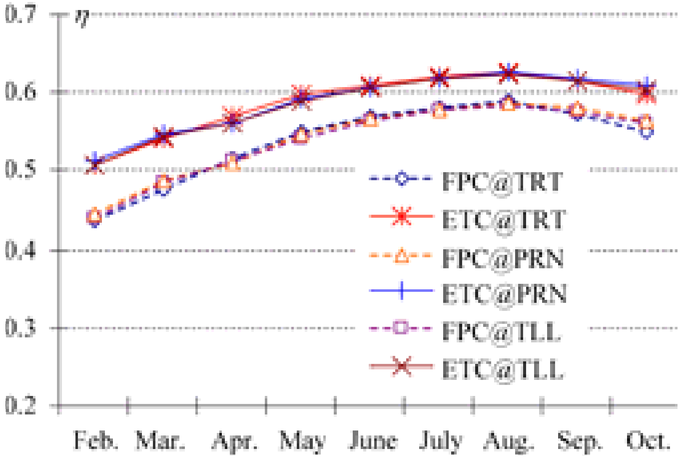

Fig. 3. Relationship between average daily efficiency and month.

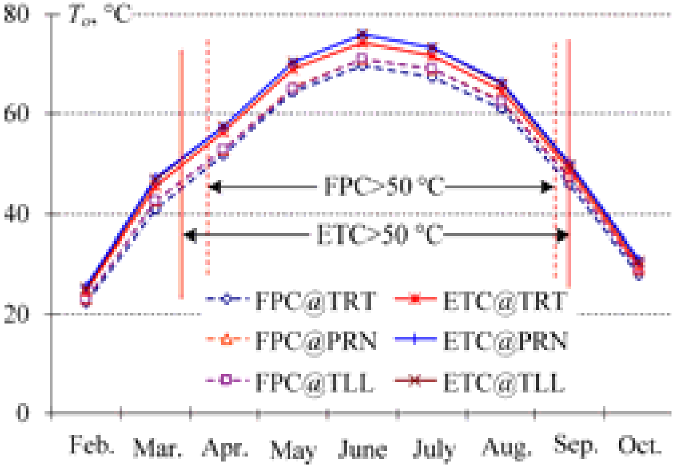

Fig. 4. Behaviour of possible output temperature without additional heating.

We can conclude that in the high latitudes and cold climate of Estonia, use of an ETC has its advantages. Whether this usage is economically justified remains open to analysis.

4. Increasing the productivity of DHW systems

4.1. Discrete tracking

Productivity will be increased if it is possible to prolong the daily active period of operation. The best method should ordinarily be radiation tracking, but Estonian conditions, with their significant share of diffuse radiation, mean exact tracking is meaningless. Here, as ETCs and FPCs both have $(\tau\alpha)/(\tau\alpha)_0$ curves nearly independent of the attack angle in the range of $0<\Theta<65°$, precise tracking therefore isn't necessary and it is sufficient to use discrete tracking in two positions [6]. In the morning the (southerly-facing) collector should be deflected eastward and in the afternoon, westward (Fig. 5).

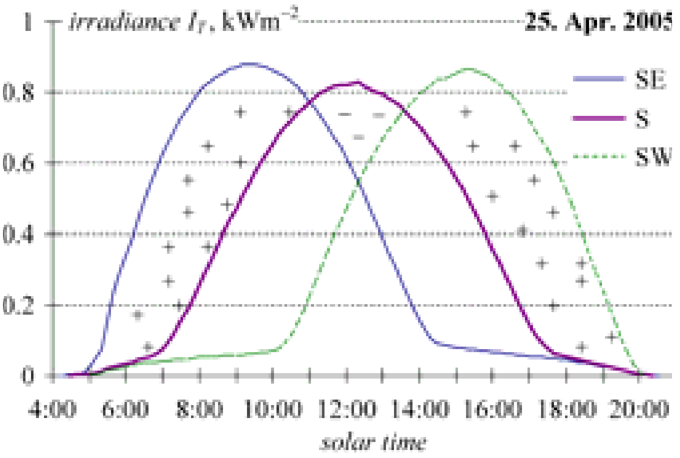

Fig. 5. An experimental recording showing gain of two-positional tracking; deflection angle ±45°.

The areas under the $I_T(t)$ line in Fig. 5 characterize the energy yield; areas marked with"+" represent energy gained, with "–" representing energy lost at noon when the attack angle will increase. On a sunny day, deflection at ±30° results in prolonging the daily operational period by four hours, achieving an energy gain of up to 30–40%. In overcast conditions there is no gain (there may even be a loss of up to 5%). Calculations under Estonian conditions show an average gain of ~15–20% per summer. A two-positional drive for discrete tracking is simple and widely used in automatically-controlled doors and gates. Their use in PV production is not problematic, but for DHW systems flexible insulated pipelines are required.

4.2. Dissection of DHW systems

Fig. 6 shows the representative performance curves [7] of solar-thermal collectors for a constant value of irradiance. All show decreasing efficiency, depending on the difference in internal, T_i, and ambient, T_a, temperatures. Curve a) represents a collector with a single optical cover, while curve b) belongs to an ETC. It is apparent that at low internal temperatures (or high ambient temperatures), efficiency of the simple collector is higher and the absorber area used more effectively (*stage* I), meaning that it is appropriate to divide the DHW system into two (or more?) operational stages (Fig. 7) [8, 9].

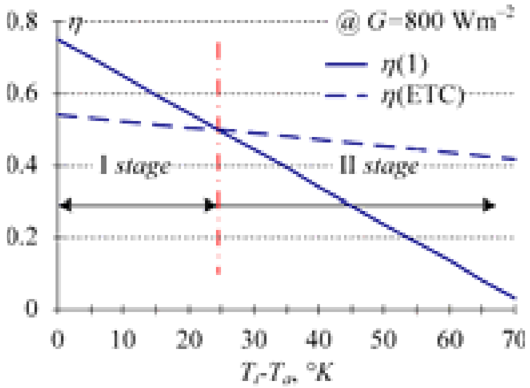

Fig. 6. Performance curves of different solar-thermal collectors.

In the first stage, the single optical cover warms the initially cold heat carrier (water) up to 25–35 °C, which is then used as an input for the second stage, where a double cover or ETC increases the temperature to its final level. Using the same absorber area, $A_1+A_2= A$, productivity will increase by ~15% in Estonian conditions [8]. This technique is valid only for DHW systems, where hot water is exchanged with cold. It is not valid for heating systems which operate using the same water and the temperature of backflow is rather higher, at 35–40 °C. The two separated storage tanks (electrical boilers?) shown in Fig. 7 are not necessary, as if a single tank has two inlets and two outlets, the stagnation of water separates the stages automatically. Of course, additional heating is necessary only for the second stage. The FPC used in this study (the SK-500) is not the best for use in the first stage, with better results potentially achieved with a simple home-made K-16, as recommended by AEE (Arbeitsgemeinschaft Erneuerbare Energie, Austria). This may be problematic when it comes to retailers, who prefer to sell equipment as entire systems. Each producer attempts to make their own “best” collector, which is not really the best method for the complex heating of domestic hot water.

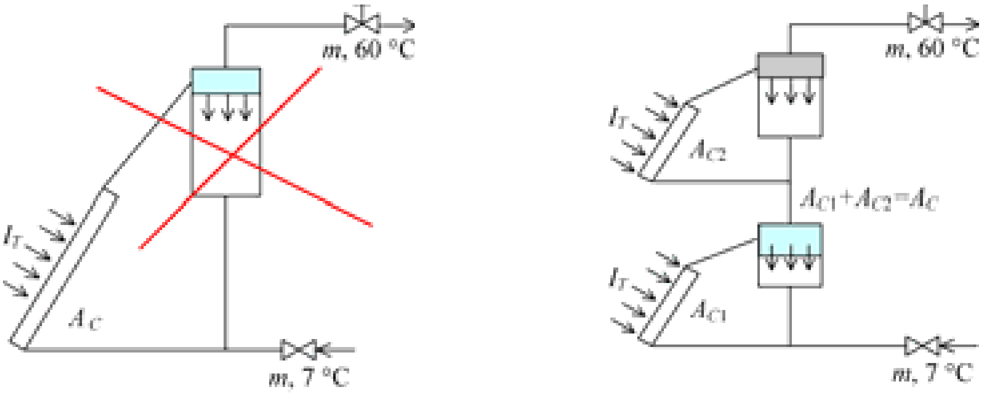

Fig. 7. Dissection of a DHW to obtain increased efficiency.

5. Summary

The development of solar energy-based heating technologies in Estonia has passed its early phase of development and moved into commercialization. This spontaneous development has popularised the use of evacuated tubular collectors, with the simulation carried out in this study proving their advantages (in terms of productivity) in the cold Estonian climate. Two methods have been presented which aim to increase their energy yield under such conditions of an extremely non-uniform energy resource.

Acknowledgments

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