Thermally activated building systems for nearly zero energy communities: Influence of the solar thermal heat generation

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Abstract

To achieve national and international climate goals, also the greenhouse gas emissions from the building sector must be reduced. One option is the use of renewable energies, which must be stored. Thermally activated building parts (TABS), e.g. solid concrete walls with integrated capillary tubes, are a potential heat storage. In order to investigate the potential for electric demand side management a representative dwelling, equipped with an electric heat pump, a solar thermal collector and TABS is used to investigate the influence of size and orientation of the solar thermal collector. It was found that the orientation of the collector is a major driver, as expected, but also unfavourable orientations, to the West and East, still lead to a significant use of solar thermal heat. Increasing sizes of the solar thermal collector also lead to reduced electric demands, but with a clearly asymptotic behaviour. The potential for demand side management is investigated using a time variant tariff, representing the time variant carbon intensity. The highest potentials can be found with the solar thermal collector oriented to the West and East. In contrast the southern orientation leads to a higher carbon tax. It was also shown that the distribution of the tariff is rather constant for the size and the orientation of the collector. Furthermore, a formula was derived to estimate the total annual electric demand of a building, depending on the size and orientation of the solar thermal collector.

Introduction

In order to reduce greenhouse gas (GHG) emissions from operating buildings further insulation or renewable energies can be used. Research shows that in moderate climates further insulation, above current standards, leads only to neglectable savings during the lifecycle, see Gauer and Kurzrock (2019), Vogdt and Helbach (2015) or Loewe et al. (2010). Thus, the use of renewable energies is a promising alternative. Renewable energies, like solar thermal heat, must be stored in order to be used for heating at later date. This storage is done using waterfilled metal cylinders, which grow disproportionally in size with an increasing use of renewable energies. One promising storage technology is the active thermal use of the solid framework already in place with capillary tubes at the centre of the bearing layer as thermally activated building systems (TABS). Those not only have the ability to incorporate RE into heating systems, but also allow for further energies, alike excess electric energy from the public grid, utilising either an electric heat pump or a heating rod. For their incorporation it is inevitable to estimate the potentials for reducing GHG emissions and demand side management of such heating systems.

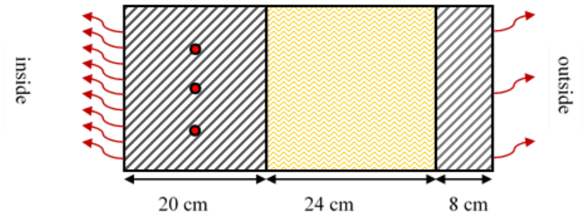


Figure 1: Layer composition of the TABS (cross section with solid load bearing layer with piping, insulation and outer layer from left to right).

In the following the influence of the size and orientation of a solar thermal collector on the heating system with TABS and the resulting electric demand is investigated.
The succeeding investigation will cover only thermal aspects and assume the TABS to be produced as precast concrete elements. Discussions regarding mechanical aspects of TABS can be found e.g. in Schmitt and Pahn (2019).

Simulation / Methodology

Used sample building

The influence of the solar thermal collector is investigated using a representative residential building for Central Europe, as shown in figure 2. The effective area is 140 m² and split equally between the two floors. The northern exterior walls of the building are turned into TABS and sum up to 47 m². The tubes, turning the walls into TABS, are made of PE and placed in the centre of the bearing layer of the external wall with a spacing of 10 cm. Further details of the building, e.g. the properties of other building parts, can be found in Heimrath and Haller (2007).

The heat demand of the building is covered using a solar thermal vacuum collector assisted by an electric air heat pump. The heat generated is transferred to a water filled buffer storage of 300 l. The heat demand is then covered suppling the heat to the TABS and a floor heating system.

An identical building, but without TABS, is used as a reference.

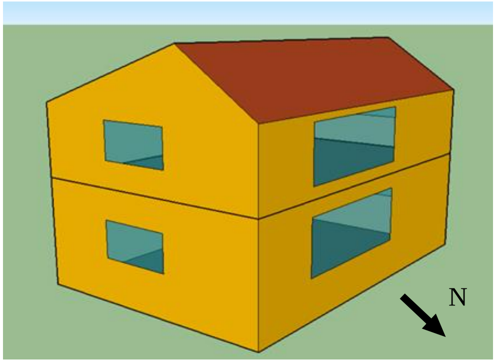


Figure 2: Representative residential building.

Investigated cases

As the orientation and shape of buildings can be influenced or to some extend be given by order during the planning of new districts also the available areas for solar collectors – electric or thermal – are influenced. Thus, the influence of the size and the orientation of the apparatus area of the solar thermal collector is investigated. While the apparatus area potentially influences the heat production, the size of the TABS potentially influences the heat storage capacity. From this the following parameters were derived, see table 1. The bold values represent the reference cases without TABS.

Table 1: Investigated scope of parameters

Solar thermal collector		TABS
Apparatus area [m²]	**Apparatus orientation [-]**	**Area activated [% of the northern wall]**
20, 30, **40**, 50	**W, S, E**	25, 50, 100

Methodology

In order to generate thermal and electric load profiles a thermal simulation of the buildings is used. To do so, the above building and the heating system is modelled using TRNSYS 17. The simulation of the TABS is done using MatLab and is coupled to the building simulation, as described in Javanmardi, Bavani and Pahn (2017). This allows to monitor all temperatures of the TABS and vary nearly all parameters freely.

The investigation is split into two separate parts. First the underlying mechanisms will be explained in brief using one case, with a fully activated northern façade (100%) and 40 m² south facing collector area, and a refence case without TABS. In the second part the influence of the parameters defined in table 1 are described. In fact, the heat generation, the electric demand and the annual costs of the cases are investigated.

In order to evaluate the impact on the electric grid a time dependent electricity rate is used. The tariff is based on an energy price of 0.3 €/kWh$_{el}$ and a time variant tax, depending on the hourly carbon intensity. The tax is derived from the carbon intensity of the German electric grid in 2019. To do so the hours of the year are sorted based on their carbon intensity and split into four groups of equal length. While the electric energy demand in the quarter with the highest intensity is charged with an additional tax of 600 €/kg-CO$_2$-eq. The quarter with the lowest carbon intensity is credited with 600 €/kg-CO$_2$-eq.. The other two quarters are charged in the manner, but with half the tax or credit respectively. From an average carbon intensity of 0.397 kg-CO$_2$-eq./kWh$_{el}$ taxes of ±0.238 and ±0.119 €/kWh$_{el}$ result. In combination with an energy price of 0.3 €/kWh$_{el}$ effective rates of 0.538, 0.419, 0.181 and 0.062 €/kWh$_{el}$ result.

Underlying mechanisms

The introduction of TABS to the heating system results in a further heating surface, in addition to the floor heating, and an increased thermal storage capacity. The first one results in reduced transmission heat losses, as the external walls are heated. The additional storage allows to increase the heat generated by the solar thermal collector. This also leads to lower buffer storage temperatures during the operation of the solar thermal collector, reducing from ab. 80°C to ab. 40°C. Thus, more solar thermal heat can be generated due to a reduced average supply temperature to the solar thermal collector during its operation. Further details on these mechanisms can be found in Gauer and Pahn (in press). This increased utilisation of solar thermal heat leads to a reduced heat production of the heat pump, see figure 3. Parts of the solar thermal heat are used to cover additional thermal losses, e.g. resulting from slightly increased room air temperatures. Never the less the heat production of the heat pump is reduced by ab. 1,500 kWh$_{th}$/a or ab. 30%. Furthermore, the solar share of generated heat is more than doubled from ab. 26% to ab. 53%.

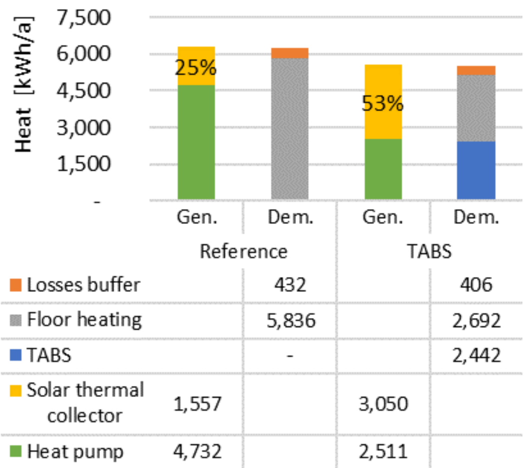
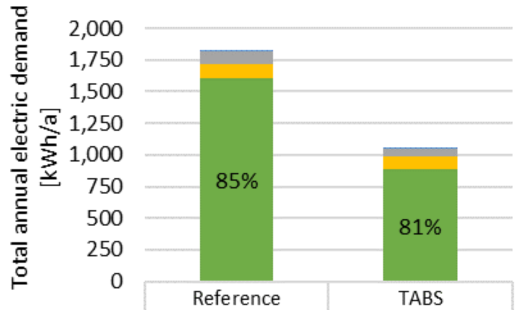


Figure 3: Heat generation and demand.

This shift in heat generation also results in a shift in electric demand. As the heat pump is the major electric consumer the total electric demand is reduced by ab.

800 kWh$_{el}$/a or 40%, see figure 4. Thus, it can be concluded that the reduction in electric consumption is based on a shift in heat production, which is mainly possible to an increased storage capacity. The additional operation of the pumps of the solar thermal collector and the TABS only lead to a neglectable electric demand.



	Reference	TABS
Control	9	9
Floor heating	105	62
TABS	-	4
Solar thermal collector	115	102
Heat pump	1,601	883

Figure 4: Electric energy demand.

As indicated above these results are only valid for a south-facing collector of 40 m² and a fully activated northern facade. By varying the input parameters, as shown in table 1, more general results can be achieved. These results then allow to predict the heat production and the electric demand in an early stage of the planning. This might then be used to make legal requirements in order to optimise the use of local renewable energies.

Discussion and result analysis

As described above the solar thermal heat generation is the major driver to reduce the annual electric demand. Thus, figure 5 shows the annual heat generation of the solar thermal collector with respect to the parameters defined in table 1. It can be seen that the solar heat generated is significantly increased by 500 to 1.500 kWh$_{th}$/a when using TABS, compared to the refences. In contrast to the orientation of the collector, the size of the TABS has only a smaller influence on the solar thermal heat generation varying only up to 200 kWh$_{th}$/a for a southern orientation. Collectors facing East or West show only neglectable differences, when varying the actived area. Never the less all variation with collectors facing West are superior to te variations with collector facing East. In terms of the refences, it is striking that a East or West facing collector results in about the same solar gains as a south facing collector without TABS. Based on the mechanisms above it can be seen, that the use of TABS is more beneficial if more solar thermal heat is available, as the comparison of the references with the cases investigated shows. Furthermore, the well-known dependency on the orientation of the collector can be seen clearly. Also, the asymptotic behaviour can be found in literature.

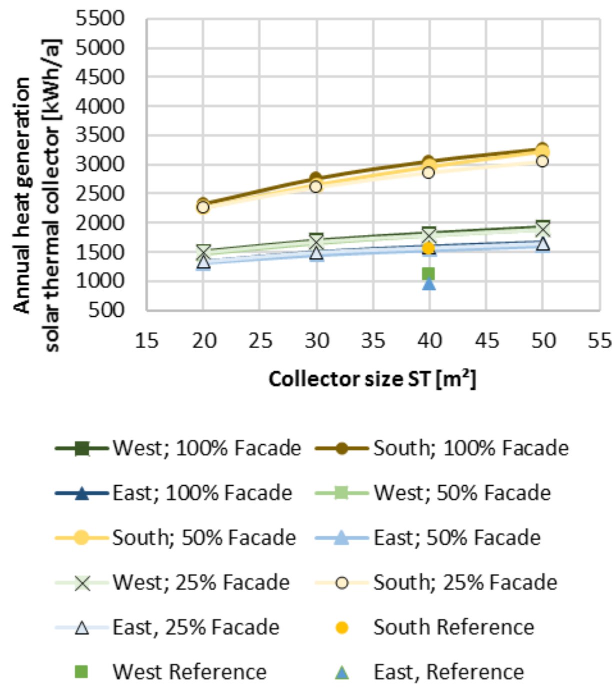


Figure 5: Heat generation: Solar thermal collector.

Due to the increased solar thermal heat generation with increasing collector sizes the heat generated by the heat pump is decreasing, also with an asymptotic behaviour, see figure 6. Compared to the solar thermal generation the generation of the heat pump varies more than double within the orientation of the collector, up to 500 kWh$_{th}$/a. Notable is also the generation for south facing collector is nearly identical for utilising 50 and 100% of the northern façade. By reducing the TABS to 25% of the façade area the heat generation by the electric heat pump is increased by 500 to 600 kWh$_{th}$/a. The same also applies for the other orientations, but with a smaller impact. This effect results from the fact that with smaller TABS the storage capacity is limiting, while with bigger TABS the solar supply is the limit.

Comparing both heat generations it is striking that the solar thermal generation is nearly independent of the size of the TABS. Which results from the fact, that the solar thermal supply is limiting further reductions of heat production by the eletcric heat pump and not the requiered storage capacity for solar thermal heat. In contrast the smallest size of TABS leads to a significant increase in heat production of the electric heat pump, resulting from the reduced available thermal storage capacity.

It can be seen that the heat generation of the heat pump is reduced by ab. 500 kwh$_{th}$/a, comparing Eastern and Western orientations. This finding is independent of the size of the solar thermal collector and is based on the time shift resulting from the use of the TABS. It is further and in detail discussed in Gauer and Pahn (in press).

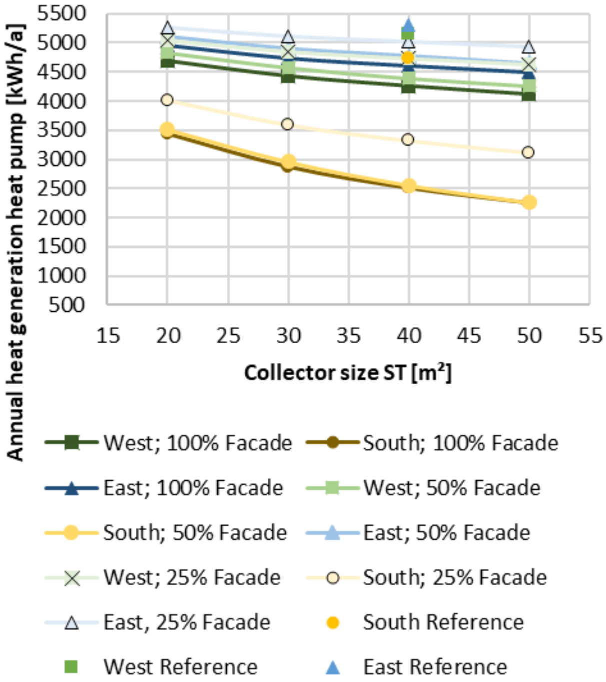


Figure 6: Heat generation: Heat pump.

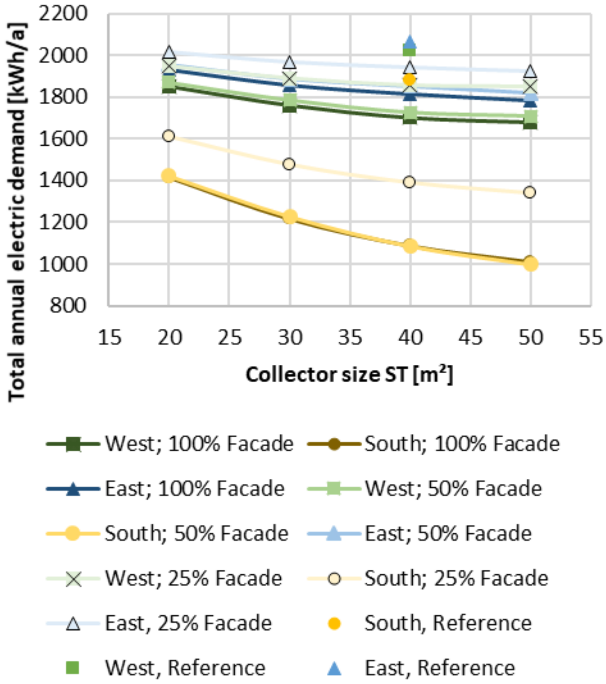


Figure 7: Total annual electric demand.

From this shift in heat generation, depending on the parameters chosen, the annual electric demand of the whole heating system can be derived, as shown in figure 7. It can be seen clearly that the electric demand strongly corresponds with the heat generation of the heat pump, see fig. 5. It can also be seen that for collectors oriented to the South the asympotic behaviour starts at bigger collector sizes of more than 50 m². While the other orientations show a clearly asymptotic behaviour within the investigated range, resulting in small to neglectable reductions in electric demand for aparatus areas of more than 40 m².

Presuming the residential building, as shown in figure 2, also a traditional saddle roof allows for sufficient surface area to install the collector sizes found. Additional surface area for a PV is available or might be even increased by using a shed roof.

With respect to the references, every utilisation of TABS is beneficial, considering 40 m² of ST. This also applies to other colector sizes, but is not displayed for a clearer display. The ssavings of electric energy is mainly due to the increased solar thermal heat generation using TABS.

With respect to the electric demand, it can also be seen that less beneficial orientations utilising TABS lead to similar electric demands as a more potent south facing collector, as both result in an annual electric demand of ab. 1,850 kWh_{el}/a.

From this a formula can be derived, which allows to estimate the annual electric demand of the heating system of the building ($E_{el,a}$). In the following two polynomials are used in order to represent the size (A) and the orientation (o) of the collector. In addition, it is assumed that sufficient storage capacity is available, thus the TABS using only 25% of the northern façade (ab. 12 m²) where not considered. (1) can be derived by interpreting the orientation with South = 0, West = -90 and East = 90. This definition makes the formula also applicable in the southern hemisphere.

$$E_{el,a} = (-1.67^{*}o^{2} - 4{,}422^{*}o + 26{,}670) * A^{2} * 10^{-5} + (-2.31^{*}o^{2} - 36.4^{*}o + 32{,}918) * A * 10^{-3} + (21.1^{*}o^{2} - 93.33^{*}o + 1{,}974{,}300) * 10^{-3}. \quad (1)$$

To evaluate the impact of the orientation and size of the solar thermal collector the above defined carbon tax on greenhouse gas emissions is investigated. As figure 8 shows the annual costs, incl. the carbon tax, show the same dependencies as the electric demand, see figure 7. This is due to the fact, that the tax not only leads to increased costs, but can also leads to credits. Therefore, the energy rate is the dominating summand. This influence may be reduced with a lower energy rate and higher carbon tax.

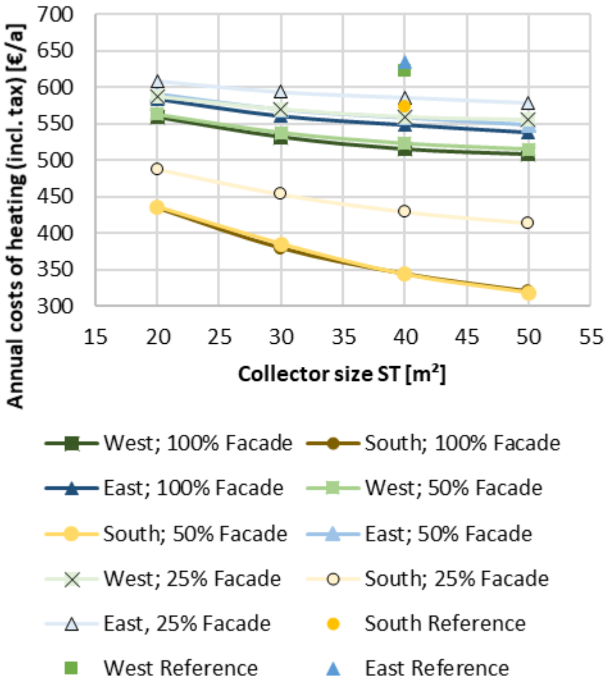


Figure 8: Annual costs of heating.

In order to evaluate the contribution to demand side management the average specific carbon tax is investigated. As stated above it increases the specific costs while times with high GHG emissions, thus a higher av. carbon tax represents a less favourable electric demand. Figure 9 shows clearly that for orientations to the East and West the use of TABS leads to a reduction, compared to the corresponding references. In contrast the southern orientation leads to higher av. carbon taxes, thus a less favourable structure of demand than the reference. From this it can be concluded, that in terms of demand side management, it is favourable to orient the solar thermal collector to the East or West.
Nevertheless, the total annual carbon tax is between 10 and 20 €/a and is proportional to the collector size for the southern orientation. While the other orientations lead to lower carbon taxes of 1 to 5 €/a, nearly independent of the size or orientation.

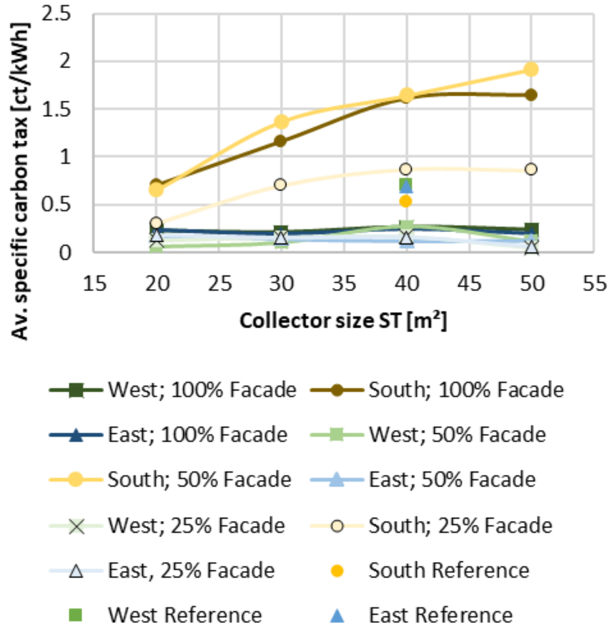


Figure 9: Specific carbon tax.

A more detailed investigation on the carbon tax and electric demand was done, in order to better understand the structure of the resulting annual tax. Figure 10 shows the electric demand of the heat pump, with respect to the carbon tax rates and a variation of the collar thermal collector. While the apparatus area of 40 m² and a fully activated façade is considered, the orientation is varied. It can be seen that ab. 30% of the annual electric demand is credited with the full tax rate and ab. 23% with the reduced tax rate. The full or half tax must be paid for 25 to 30% and 19% of the electric energy used. For changing collector sizes only neglectable changes result.

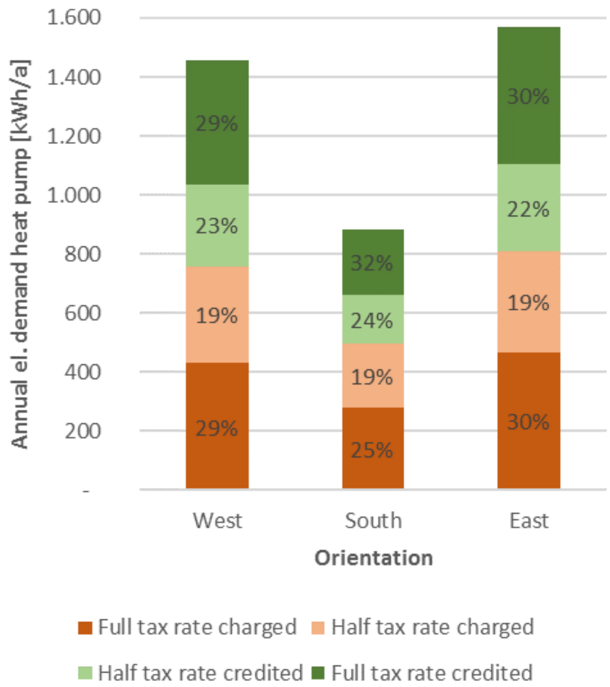


Figure 10: Annual electric demand with respect to the carbon tax.

Conclusion and outlook

The research shows that TABS lead to a reduction of the total annual electric demand, compared to references without TABS. The orientation of the solar thermal collector of a heating system is not only influencing the solar thermal heat generation, but also the annual electric demand. Based on the used distribution of GHG emissions of the electricity used orientations of the solar thermal collector to the East and West lead to lower GHG emissions, resulting in a lower taxation. Orientations to the South lead to increased specific GHG emissions. In contrast the total annual taxation for a southern orientation is 10 to 4 times higher than the other orientations. The taxation results from a structure where ab. 30% of the electric energy is used during the most favourable respectively unfavourable times and ab. 20% during times with reduced tax rates. This structure is independent from the size of the TABS, the collector size and orientation.

Furthermore, a formula was derived, which allows to predict the annual electric consumptions, depending on the size and orientation of the solar thermal collector.

The impact of TABS might be increased by using a control strategy, which accounts for the time variable tariff, alike shown in Bauer et al. (2017). The integration of on site or local renewable electric energies, like from PV or wind, into demand side management can be achieved by adapting the tariff.

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