Antti Lehtilä (VTT)
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Experimental refinement into the TIMES STS storage formulation

Experimental improvements implemented for the TIMES STS storage formulation are presented below for discussion. These improvements have been inspired by the paper by Kotzur et al. (2018)[1], where a slightly different approach was described for linking typical representative days (such as seasons in TIMES) with each other. Their approach is illustrated in Figure 1, showing the states of the time steps g within the seasons i, and the "inter-period" states at the beginning and end of each season i (with some self-discharge effect also shown).

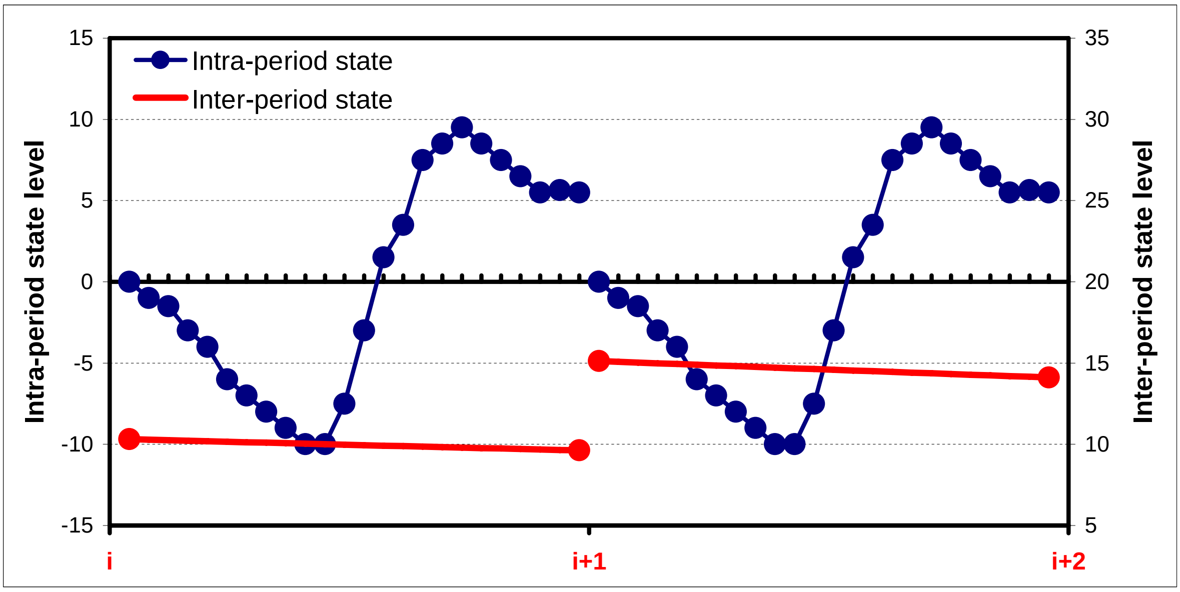

Figure 1. Separation of the storage state into two states on two different time layers (e.g. DAYNITE and SEASON), according to Kotzur et al. (2018).

The paper also states that the storage capacity D_s should limit the state of charge (SOC) as follows:

$$0 \quad \leq \quad SOC_{s,i}^{inter} \times (1-\eta_s^{self}\Delta t)^{Ng} + SOC_{s,i,g}^{intra} \quad \leq \quad D_s \quad \forall i,g \qquad (1)$$

One can see from Figure 1 and Eq 1 that in the formulation by Kotzur et al. the variation in the total storage level SOC can occur around the seasonal state SOC^{inter} , both upwards and downwards, as long as the total value of the SOC remains non-negative. Consequently, the intra-seasonal state of charge, SOC^{intra}, can have both positive and negative values. That is notably different from the original TIMES formulation, where the total storage level SOC is always assumed greater than or equal to the corresponding seasonal state of charge SOC^{inter} (VAR_ACT at the beginning of each season), because the DAYNITE variation is described by positive VAR_ACT variables on top of each seasonal state of charge. It therefore seems that the TIMES formulation might be improved by making it more flexible in this respect, by allowing the DAYNITE variation to take place around the intra-seasonal state of charge also in TIMES. The implementation of the improvement is described below, but the question whether the assumptions are indeed reasonable is left open for discussion.

[1] Applied Energy 213 (2018) 123–135. https://doi.org/10.1016/j.apenergy.2018.01.023

A. Simple Illustration of the Original STS Implementation

The original implementation of STS storage was done in 2012, with the simple objective of providing a way of modeling general timeslice storage with a single process, instead of adding storage processes at each timeslice level, which was the only way supported previously in TIMES. As mentioned above, in the original implementation any DAYNITE variation in the storage level is described by positive VAR_ACT variables on top of each seasonal (or weekly) state of charge. Consequently, the total storage level SOC^{total} was always greater than or equal to the corresponding seasonal state of charge SOC^{inter}. Moreover, the seasonal state of charge was explicitly measured only by the VAR_ACT at the beginning of each season. The assumptions are illustrated in Figure 2, for a simplified example with only SEASON and DAYNITE levels, and with three seasons.

As shown in Figure 2, the seasonal storage remains mostly unusable for any DAYNITE storage operation, because all of the variation in the DAYNITE level is effectively assumed to occur above the storage level at the beginning of the season. Moreover, any charging and discharging of the seasonal storage level must be assumed to happen evenly throughout the season in the TIMES multi-layer implementation, and that also tends to increase the required DAYNITE storage levels.

In reality, it would seem more likely that such a storage process could be operated somewhat more flexibly, utilizing even a considerable proportion of the seasonal stock also for the daily variation. In the example above, it might be reasonable to assume that in the season i one would be able to utilize up to 2 units (the amount still available at the end of the season) for the daily variation, and similarly in seasons i–1 and i+1 one would be able to utilize up to 1 unit, because these levels remain available in the storage every day throughout the seasons in question.

Indeed, the formulation of Kotzur et al. (2018) illustrated above does appear allow a much more flexible operation, without requiring that any part of the storage should remain unused during the daily operation within a season. Therefore, it would seem that the original TIMES implementation may be overly conservative in this respect, leading to some underestimation in the role of storage

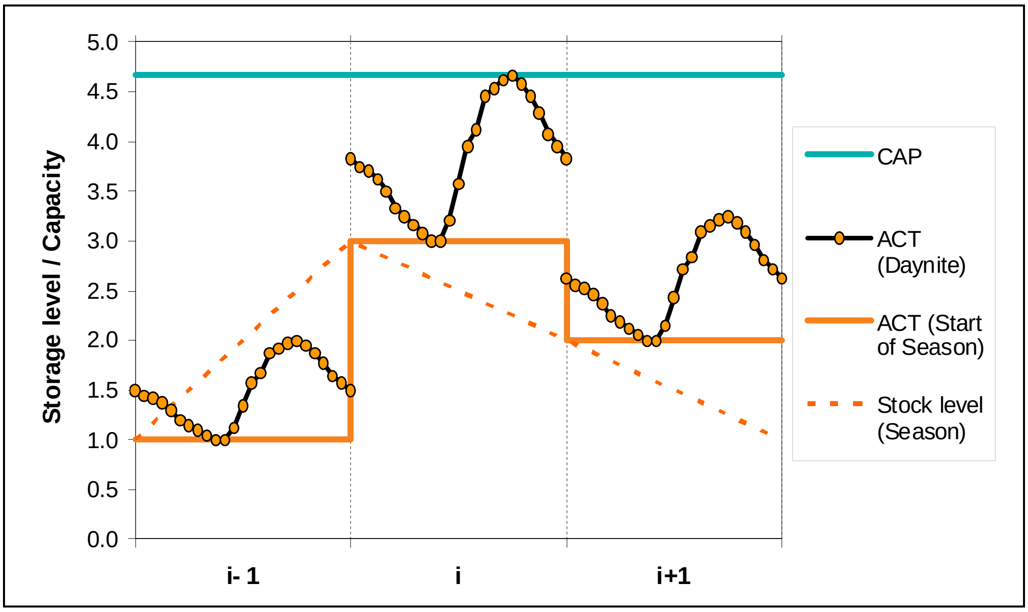

Figure 2. Illustration of the STS storage levels on the DAYNITE and SEASON levels in the original implementation. The capacity requirement for the energy storage is also shown at the top, as implemented by the EQ_CAPACT equations for storage.

technologies. Bearing in mind the increasing importance of storage in energy systems models, this issue may deserves some consideration and possibly justify enhancements to be implemented.

There is also at least one other, quite different shortcoming in the original STS implementation: In seasons with increasing seasonal storage levels, the true capacity requirements may in some cases be underestimated. That may happen if the DAYNITE variation is large in comparison to the total storage levels, and is due to the fact that the EQ_CAPACT equations are based on seasonal storage levels at the beginning of each season only (which is fine for storage operating on one level only).

An example is illustrated in Figure 3, where the seasonal DAYNITE variation is very large in season i–1, while the seasonal storage is also charged and its level is increasing. We can see that if we would take into account the seasonal storage level at the end of the season (level=3.0), the DAYNITE variation would actually require a higher capacity than what the original implementation requires. TIMES only sees that the highest overall storage level would be in season i, abut 4.7 units, while in season i–1 the overall storage level would in fact be even higher. If we would use the same assumptions for the end of season as for the beginning of season, the capacity should be as high as 7 units to accommodate the variation. However, if we allow some more flexibility, we could assume that the average DAYNITE level should coincide with the seasonal storage at the end of the season (3 units), and then the total requirement would be at least 5 units, as shown at the top of Figure 3. And that amount is still larger than the capacity assumed sufficient originally in TIMES.

As one can imagine, this issue, where the capacity requirement is underestimated in TIMES, only rarely becomes notable under the original implementation, because the DAYNITE variation would have to be quite large for the issue to become significant. However, if we would allow a more flexible storage operation, where the season level storage could be utilized also for the DAYNITE variation (as described above), this problem becomes inherently more prominent, and should be also addressed if improvements to the formulation are to be implemented.

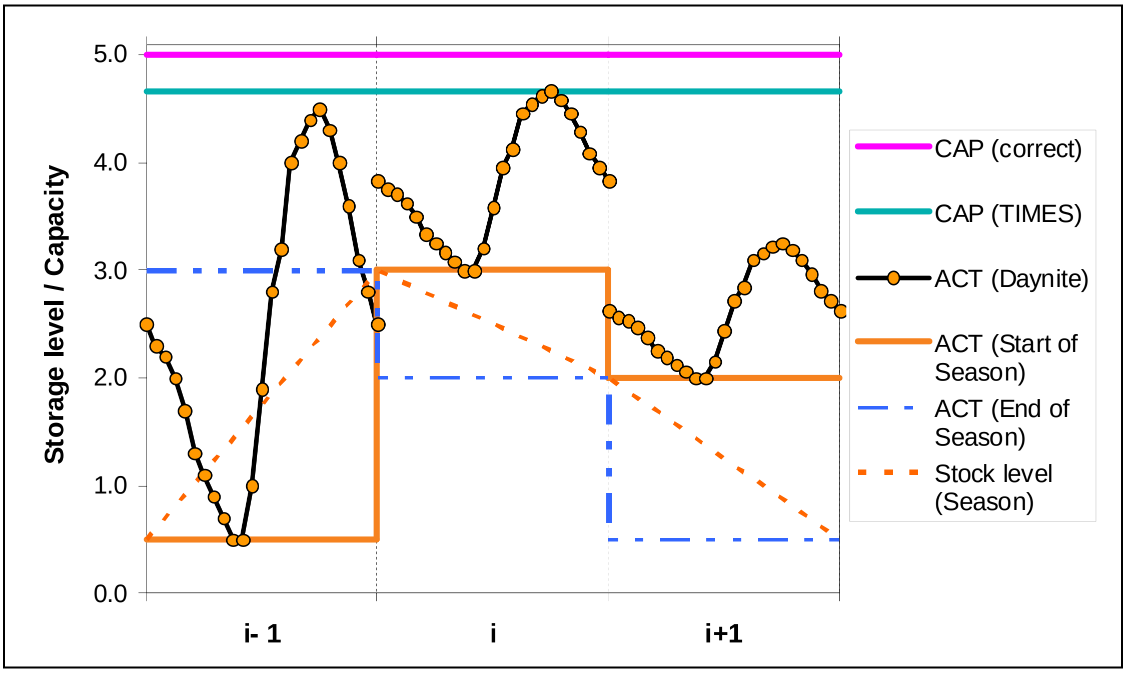

Figure 3. Illustration of a potential underestimation of the true capacity requirement of STS storage operation in the original implementation. The estimated correct capacity requirement and the requirement assumed by TIMES are shown at the top.

B. Experimental improvements into the STS Formulation

It appears clear that if we may consider it reasonable to assume such more flexible operation, the storage capacity requirement and the total losses would both become smaller, due to the total storage level required for the storage operation being smaller. The effect is illustrated in Figure 4, where the same example as was shown in Figure 2 has been simply adjusted to correspond to the assumption that the DAYNITE variation can occur around the seasonal storage level. One can see that under the more relaxed assumptions the capacity requirements are reduced, even though the storage levels can still be considered sufficient for the same operation as in Figure 2.

However, assuming that these adjustments are made, it also becomes evident that the issue of underestimating the capacity requirement during increasing seasonal storage levels may at the same time become considerably more serious, and should therefore be addressed now. For that purpose, we can implement two additional variables, defined as the additional and subtractive capacity requirement at the end of each season or beginning of season, respectively. The additional capacity requirement is positive only when the seasonal storage level is increasing, and the subtractive capacity requirement is positive only when the seasonal storage level is decreasing. In that way we can have consistent symmetrical constraints for the minimum capacity requirements under both increasing and decreasing seasonal storage levels. From the capacity perspective, the result from this correction is equivalent to shifting the DAYNITE storage levels by the increase in the seasonal level. By using the example of Figure 3, the effect of the adjustment is illustrated in Figure 5.

Note that the correction added for the seasons with increasing storage levels do not affect the storage losses, which are calculated according to the trajectory of the seasonal storage level and according to the DAYNITE levels, basically in the same manner as in the original implementation. Nonetheless, in the case of the first season of Figure 5, the average storage level and the storage losses are considerably higher than in Figure 4, because the seasonal storage level is so low at the beginning of the season and the total level is guaranteed to remain always non-negative.

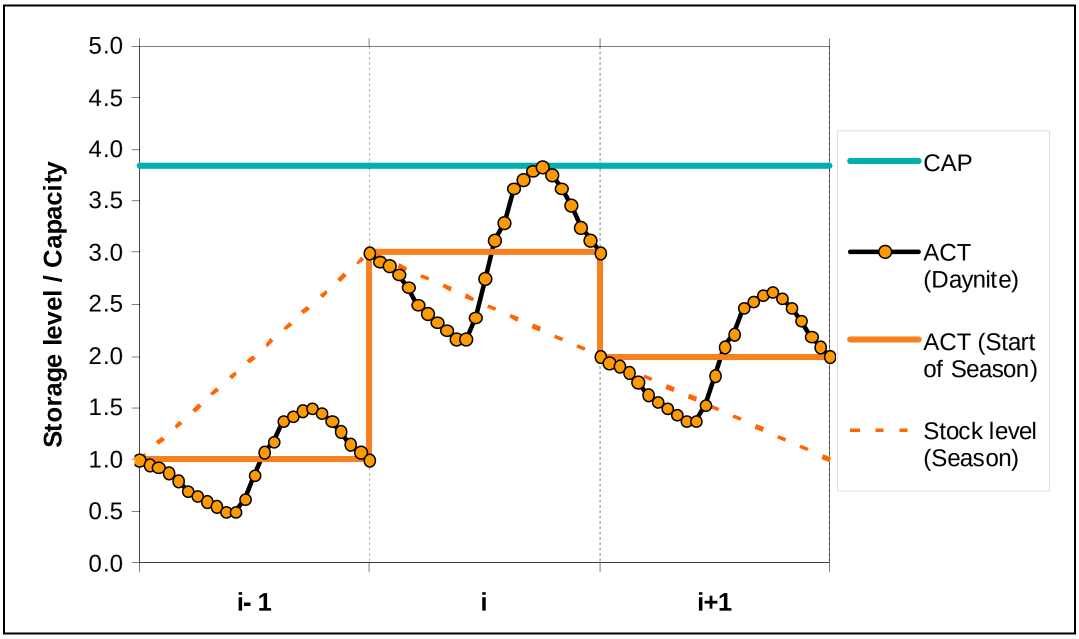

Figure 4. Illustration of STS storage operation under the suggested improvement.
The storage capacity requirement is also shown at the top.

Thus, while in the example of Figure 4 the average total storage level is only 2 during season i–1 (increasing from 1 to 3), in the example of Figure 5 the average would be 3.25 according to the improved formulation suggested to be considered for adoption into TIMES.

Mathematical summary of the improvements suggested for consideration

The modification into the STS formulation would mean that the total storage level and thereby also the capacity requirement can be reduced compared to the original formulation, if (and only if) the storage has simultaneous DAYNITE and SEASON operation. The reduction in the storage level and the capacity requirements, which would be realized according to the more flexible assumptions described above, can be summarized in a very compact way. Let's use the following nomenclature:

- VAR_ACT(ts) – the activity levels (DAYNITE, SEASON) in the original formulation
- VAR_LEV(ts) – the achieved reduction in the total seasonal activity
- VAR_ADD(ts) – additional capacity requirement due to increasing storage level
- VAR_SUB(ts) – subtractive capacity requirement due to decreasing storage level

$$VAR\_LEV(ts) = Min\left(VAR\_ACT(ts), VAR\_ACT(ts+1), \underset{RS\_BELOW(ts,s)}{Average} (VAR\_ACT(s)) \right) \qquad (2)$$

The reduction in the seasonal activity can thus be at most the minimum of the average DAYNITE activity under season ts, the seasonal activity in the beginning of season ts, and the seasonal activity in the end of season ts. The storage capacity requirement would be reduced by that same amount, unless the seasonal storage level is increasing (as described before), because in that case we might underestimate the capacity requirements if we only measure the total activity in the beginning of the season.

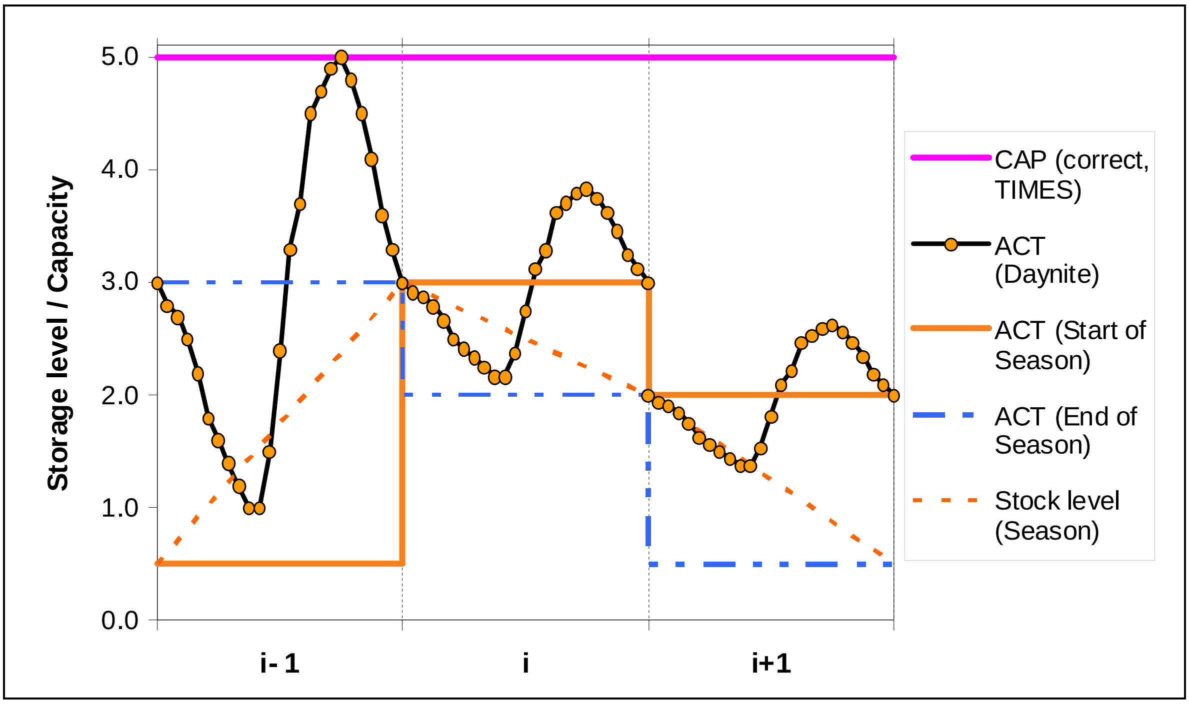

Figure 5. Illustration of STS storage operation with a large DAYNITE variation in season i–1, adjusted by shifting it up by an amount ensuring sufficient capacity during that whole season.

When the seasonal level is increasing, the additional capacity requirement VAR_ADD(ts) due to that increase can be simply calculated as the difference between the end-of-season and beginning-of-season activity levels (in the original formulation), minus the average DAYNITE activity exceeding the reduced amount, as follows:

$$VAR\_ADD(ts) = Max\left(\begin{array}{l} 0,\ VAR\_ACT(ts+1) - VAR\_ACT(ts) - \\ \left(\underset{RS\_BELOW(ts,s)}{Average}\ (VAR\_ACT(s)) - VAR\_LEV(ts)\right) \end{array}\right),\ ts \in SEASON \qquad (3)$$

The justification for the first part (the difference between the end-of-season and beginning-of-season activity) should be self-explanatory. The final term (subtracting the average DAYNITE activity exceeding the reduction in total activity), is justified by the fundamental assumption adopted for the suggested improvement, that the variation in the DAYNITE activity should cause additional capacity requirement compared to the seasonal level only to the extent the variation exceeds the average total storage level during the season, as described above (Figures 4 and 5). For example, for the example in Figure 5 we get VAR_ADD(i–1) = 3.0 – 0.5 – (2.0–0.5) = 1.0, meaning that the capacity requirements will be adjusted by assuming 1 unit higher total activity, which will ensure sufficient capacity at the end of the season. The total capacity requirement for season i–1 would thus be 0.5 – 0.5 + 4.0 + 1.0 = 5.0 (seasonal level at the beginning of the season – VAR_LEV + max. DAYNITE VAR_ACT + VAR_ADD), assuming a 100% availability factor here for simplicity.

Symmetrically, we can reduce the capacity requirement at the beginning of a season, when the seasonal level is decreasing and the average DAYNITE activity exceeds the reduction in the seasonal activity:

$$VAR\_SUB(ts) = Min\left(\begin{array}{l} \max(0,\ VAR\_ACT(ts) - VAR\_ACT(ts+1)), \\ \left(\underset{RS\_BELOW(ts,s)}{Average}\ (VAR\_ACT(s)) - VAR\_LEV(ts)\right) \end{array}\right),\ ts \in SEASON \qquad (4)$$

This adjustment (4) simply accomplishes a condition symmetric to (3) when seasonal level is decreasing, because symmetrical assumptions between increasing an decreasing seasonal levels would seem very reasonable. The three formulas (2), (3) and (4) shown above comprise all the modifications that were considered worthwhile for improving the original formulation.

The implementation would require only a few new equations on the SEASON / WEEKLY levels and a few new variables, and so it would only have a small impact on the overall model size. However, if the basic assumption behind the suggested improvement, namely that the DAYNITE variation may occur around the seasonal state of charge instead of forcing it to be above that level, is considered reasonable, the improvements suggested might have a visible impact on the role of STS storage technologies in the results of TIMES models including these kind of general storage processes.

C. Concluding Remarks

The experimental improvements described above were inspired by the recent paper by Kotzur et al. (2018), and would accomplish the following changes into the original STS formulation:

- The variation in the DAYNITE (e.g. hourly) storage levels can occur around the seasonal state of charge SOC^{inter}, which was reached at the end of the previous season and is assumed to be the starting level for the total state of charge in the current season. The minimum state of charge at any time must of course always be non-negative, but unlike in the original formulation, it can freely go below the seasonal level during individual hours of the season. However, the average level must follow the trajectory of the seasonal state of charge (e.g., it must remain constant if the seasonal level of charge is being retained unchanged).

- The total state of charge, as measured by the activity levels, is reduced compared to the original formulation, if and only if the storage has simultaneous DAYNITE and SEASON operation. The minimum capacity requirement for the storage is likewise reduced accordingly, for any such combined operation. However, there is no difference compared to the original formulation either in the total storage levels or in the capacity requirement, whenever the storage is operated as a pure DAYNITE / WEEKLY / SEASON storage.

- The storage losses are also reduced under combined-level storage operations. However, there would be no impact on the losses if we simply move some of the activity from the seasonal variables into the DAYNITE variables, which is basically how the experimental improvement has been implemented. Therefore, the losses remain consistent with the total storage levels, and compared to the original formulation, they are reduced basically in the same proportion as those levels. However, when using equilibrium losses (STG_LOSS < 0), in the original implementation the losses were actually somewhat increased if storage activity was moved from seasonal variables into DAYNITE variables, due to the seasonal equilibrium losses having been somewhat underestimated. This small distortion in the original formulation has been already fixed in TIMES, by using a more detailed loss calculation.

- The experimental formulation is also refined in order to ensure that the storage capacity is sufficient for the storage operation at all times, while the original formulation may underestimate it when the seasonal level of charge is increasing.

— Evaluation —

Users of TIMES are encouraged to evaluate the experimental improvement,
in particular as to whether the assumptions behind it can be considered reasonable,
specifically, whether it is reasonable or not to assume that the DAYNITE variation
may occur both above and below the seasonal state of charge in TIMES.

The new formulation can be enabled by the run file setting `$SET STSFLX YES`