IMBALANCE ENERGY CALCULATION

1. INTRODUCTION

This white paper describes how Market Participants (MPs) can calculate Imbalance Energy (IE) production or consumption for a given resource that responds to ISO dispatch instructions in real time. IE is measured in 10-minute intervals with respect to the Final Hour-Ahead Schedule and can be provided through any of the following services:

- Spinning Reserve (SR)
- Non-Spinning Reserve (NS)
- Replacement Reserve (RR)
- Supplemental Energy (SE)

IE is always positive from Reserves, but may be either positive or negative from SE.

This white paper assumes that the reader is familiar with the concept, the terminology, and the mechanics of the 10-minute Dispatch and Settlement design.

2. REQUIRED DATA

The following data are required to perform IE calculations:

1) The maximum ramp rate (MW/min) of the resource as registered in the Master File.
2) The Final Hour-Ahead Schedule (MW) in the previous, current, and next hours.
3) The resource Energy bids (MW, $/MWh) in the IE market for each of the IE services in the current hour.
4) The resource ramp rate bid (MW/min) in the IE market for each of the IE services in the current hour.
5) The resource time delay bid (min) for NS or RR in the current hour.
6) The sequence of acknowledged incremental dispatch instructions (MW) and their time-stamps (min) for each of the IE services in the current hour.

Data (6) are available through the Automated Dispatch System (ADS). Note that the time-stamps are rounded to the next minute mark. The time-stamp for acknowledging dispatch instructions may be different than the one for issuing or receiving instructions due to an allowed time window (two minutes) for acknowledgement. Pre-dispatched IE has an effective acknowledgement time-stamp of zero min. When previously acknowledged instructions are called off, they are automatically acknowledged after 2 minutes (rounding to the next minute mark) if no response is provided after communicating the instruction. All instructions are implicitly called off at the end of the hour unless the resource is pre-dispatched for the next hour.

3. ENERGY ACCOUNTING

This section describes how Energy is accounted for.

3.1. Scheduled Energy

The scheduled energy production or consumption is calculated based on block accounting (infinite ramp at the hourly boundary) using the Final Hour-Ahead Schedule. The scheduled energy for a resource *i* at a given hour *h* and 10-min dispatch interval *k* is given by:

$$S_{i,h,k} = \frac{S_{i,h}}{6} \quad \therefore k = 1,2,\ldots,6 \tag{1}$$

For non-ISO Metered Entities, the scheduled energy at each 10-min dispatch interval, as given by (1), constitutes the reference for calculating instructed and uninstructed energy deviations.

3.2. Ramping Energy

Ramping Energy, applicable only to ISO Metered Entities, is Instructed Energy in the first and last dispatch intervals of each hour for a linear 20-min ramp across the top of each hour. The Ramping Energy is given by:

$$RE_{i,h,k} = \begin{cases} \frac{S_{i,h-1}\,GMM_{f,i,h-1} - S_{i,h}\,GMM_{f,i,h}}{24} & \therefore k = 1 \\ 0 & \therefore k = 2,3,4,5 \\ \frac{S_{i,h+1}\,GMM_{f,i,h+1} - S_{i,h}\,GMM_{f,i,h}}{24} & \therefore k = 6 \end{cases} \tag{2}$$

where GMM_f is the ex ante Generator Meter Multiplier.

The schedule-change ramp across the top of the hour is given by:

$$r_{s,i,h,k} = \begin{cases} \frac{S_{i,h}\,GMM_{f,i,h} - S_{i,h-1}\,GMM_{f,i,h-1}}{20} & \therefore k = 1 \\ 0 & \therefore k = 2,3,4,5 \\ \frac{S_{i,h+1}\,GMM_{f,i,h+1} - S_{i,h}\,GMM_{f,i,h}}{20} & \therefore k = 6 \end{cases} \tag{3}$$

and it is not limited by the maximum ramp rate of the resource.

Ramping Energy is constant, does not depend on other dispatch instructions, and has an effective price of $0/MWh. Therefore, for ISO Metered Entities, the scheduled energy at each 10-min dispatch interval, as given by (1), plus the Ramping Energy, as given by (2), constitutes the reference for calculating instructed and uninstructed energy deviations.

3.3. Dispatch Instructions

Dispatch instructions are incremental power output (MW) instructions that refer initially to the Final Hour-Ahead Schedule (FHAS). Further dispatch instructions refer to previously acknowledged instructions, as shown in Figure 1.

Instructions remain in effect until they are explicitly called off or until the end of the hour where all instructions are implicitly called off. All implicit instructions, including Ramping Energy instructions, are acknowledged in full and immediately. Instructions that are explicitly called off are also acknowledged in full and immediately.

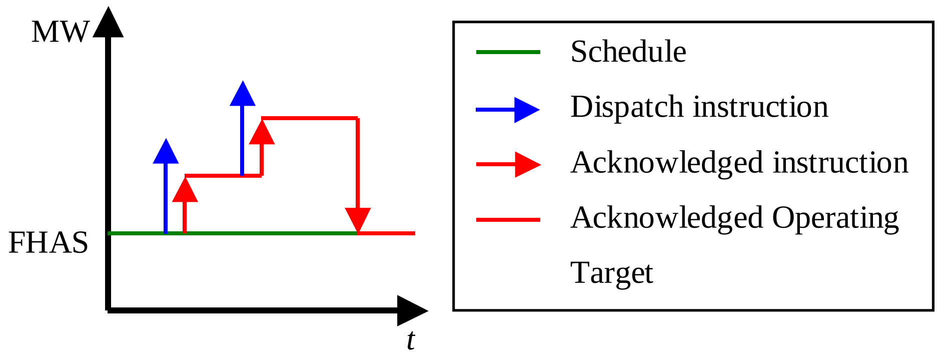


Figure 1. *Dispatch instructions*

3.4. Acknowledged Operating Target

The acknowledged instructions determine the Acknowledged Operating Target (AOT), as shown in Figure 1. The AOT is the algebraic sum of the resource schedule and all acknowledged incremental dispatch instructions, which have been issued to that resource since the beginning of the current hour. Therefore, the AOT is the output level that would be achieved if the resource could respond immediately (with no delay and with infinite ramp) to all effective dispatch instructions. Since the effective instruction times are rounded to the next minute mark, it is sufficient to track the AOT on a minute-by-minute basis.

3.5. Acknowledged Operating Point

The Acknowledged Operating Point (AOP) is the expected trajectory of the resource output over time. It is derived from the AOT and the relevant time delays and ramp rates. The time delay (applicable only to NS or RR) is considered only for the first acknowledged dispatch instruction of the relevant service in the hour. In that case, the AOP does not change until the acknowledgement time plus the relevant time delay.

After the time delay expires, the AOP ramps to the AOT with the relevant ramp rate and then remains there until the AOT changes again. The relevant ramp rate is the ramp rate bid for the corresponding service, or the 20-min linear scheduling ramp across the top of the hour. If there are several services ramped simultaneously, the total ramp of the resource is limited by the maximum ramp rate. In these cases, specific rules apply on which service has delivery priority. Furthermore, the AOP is always limited by the resource output capacity.

Given a service priority, it is simpler to calculate the AOT, AOP, and IE by service individually. The AOP can be derived either analytically or by numerical integration. Analytically, the AOP can be derived by calculating the time index of each breakpoint. Breakpoints (ramp changes) occur when the AOT changes (after any time delay) and when the AOP reaches the AOT. It is much simpler to derive the AOP by numerical integration. This will require the calculation of the AOP for each service *m* in priority order at each increment of time, as follows:

$$AOP_m(t+\Delta t) = \begin{cases} 0 & \therefore t+\Delta t \le t_f + t_{Dm} \\ \min\left(AOT_m(t),\, AOP_m(t) + r_m(t)\Delta t\right) & \therefore AOT_m(t) > AOP_m(t) \\ AOT_m(t) & \therefore AOT_m(t) = AOP_m(t) \\ \max\left(AOT_m(t),\, AOP_m(t) - r_m(t)\Delta t\right) & \therefore AOT_m(t) < AOP_m(t) \end{cases} \tag{4}$$

where t_f is the timestamp for the first acknowledged instruction from service *m* in the current hour, t_{Dm} is the corresponding time delay (if applicable), the AOT is the sum of acknowledged instructions (AI) from the beginning of the hour

$$AOT_m(t) = \sum_{t=0}^{t} AI_m(t) \tag{5}$$

and the ramp rate is the one bid for the service (r_m), unless limited by the maximum ramp rate of the resource ($r_{\max}$), as follows:

$$r_m(t) = \begin{cases} \min\left(r_m,\, \max\left(0,\, r_{\max} - r_s(t) - \sum_{j=1}^{m-1} r_j(t)\right)\right) & \therefore \left(AOT_m(t) - AOP_m(t)\right) r_s(t) > 0 \\ \min\left(r_m,\, \max\left(0,\, r_{\max} - \sum_{j=1}^{m-1} r_j(t)\right)\right) & \therefore \left(AOT_m(t) - AOP_m(t)\right) r_s(t) \le 0 \end{cases} \tag{6}$$

where the schedule-change ramp (r_s) is given by (3).

Equation (6) assumes that there are no services simultaneously ramping in opposite directions. This assumption is true because in these cases energy is instantaneously converted from out-ramping services in inverse priority order to in-ramping services in priority order so that any remaining ramping services all ramp in the same direction.

The total AOT for the resource is given by

$$AOT(t) = S + \sum_m AOT_m(t) \tag{7}$$

and the total AOP for the resource is given by

$$AOP(t) = S + \sum_m AOP_m(t) \tag{8}$$

3.6. Residual Imbalance Energy

The AOP for Residual Imbalance Energy (RIE) can also be calculated by (4). The AOT for RIE is zero, i.e., RIE is always an out-ramping service. There are two types of RIE: RIE due to out-ramping services from the previous interval in the same hour, and RIE due to out-ramping services from the previous hour. For the first type (in-hour RIE), the AOP can be calculated per service as a different service, but with the same ramp rate, possibly limited according to (6). Although in-hour RIE can be calculated per service, it should be aggregated to a total for settlement purposes.

For the second type (previous hour RIE), the AOP should be calculated for the total RIE (not by service) and with a ramp rate given by

$$r_{RIE}(t) = \begin{cases} \max(r_{RIE}, r_{\max}) & \therefore AOP_{RIE}(0)\, r_s(t) < 0 \\ \dfrac{|AOP_{RIE}(0)|}{10} & \therefore |AOP_{RIE}(0)| \le \dfrac{|S_h - S_{h-1}|}{2} \\ \max(r_{RIE}, r_{\max}) + |r_s(t)| & \therefore |AOP_{RIE}(0)| > \dfrac{|S_h - S_{h-1}|}{2} \end{cases} \quad (9)$$

where r_{RIE} is the total of all the ramp rates of the out-ramping services that created the RIE.

The initial AOP ($AOP_{RIE}(0)$) is determined by energy conversions according to the boundary conditions.

3.7. Boundary Conditions

As the AOP is integrated using (4) for all services in priority order, several boundary conditions may apply. For ISO Metered Entities, in the first interval, if $|AOP| > |AOT|$, where the resource AOT and AOP are given by (7) and (8), respectively, out-ramping services extinguish in priority order when the AOT is reached, except the last service that may need to pick up any Ramping Energy overlap. Therefore, the ramp rate for that service (usually RIE) switches to $|r_s(t)|$. Similarly, for ISO Metered Entities, in the last interval, if $|AOP| > |AOT|$, the last service may be partially reduced with a ramp rate equal to $|r_s(t)|$ to make room for any Ramping Energy if the resource capability limit is reached.

Several other boundary conditions may apply at minute marks:

- AOTs may change due to acknowledged instructions;
- new services may be added to the priority list due to acknowledged instructions;
- services may be deleted from the priority list if fully ramped out;
- energy may be converted from out-ramping services in inverse dispatch priority order to in-ramping services in dispatch priority order;

Additional boundary conditions may apply at the top of each interval:

- out-ramping services may be partially converted to RIE, down to their corresponding AOT; if there exist both previous-hour RIE and in-hour RIE, they are tracked separately, but for settlement purposes they are both considered in-hour RIE;
- RIE from the previous hour may partially vanish (it will become Uninstructed Energy) at intervals other than the first for the portion that lies within the schedule change.

- a schedule-change ramp may become active during the first or last interval of the hour;
- services may be converted to RE in the fifth interval in inverse dispatch priority order if the resource capacity limit becomes binding;
- The initial AOP ($AOP_{RIE}(0)$) for RIE from the previous hour is determined at the top of the hour as the difference of the resource AOP minus the schedule, for Non-ISO Metered Entities, or the schedule change midpoint, for ISO Metered Entities, minus the AOTs of in-ramping services (usually pre-dispatched).

3.8. Imbalance Energy

The Imbalance Energy (IE) can be calculated by service and interval as the integral of the corresponding AOP applying the trapezoidal rule of integration as follows:

$$IE_{m,k} = \int_{t_{k-1}}^{t_k} AOP_m(t)\,dt \approx \left(\frac{1}{2} AOP_m(t_{k-1}) + \sum_{t_{k-1}+\Delta t}^{t_k-\Delta t} AOP_m(t) + \frac{1}{2} AOP_m(t_k) \right) \Delta t \qquad (10)$$

A sufficiently small time increment, e.g., Δt = 1 sec, should result in acceptable accuracy.

3.9. Service Priority

The dispatch priority among the various Imbalance Energy types is as follows:

1) Ramping Energy; RE is constant irrespective of other instructions.
2) Chronological, i.e., earlier instructions have priority over later instructions.
3) Price, i.e., simultaneous IE dispatched instructions are dispatched in merit order (incremental instructions at increasing prices and decremental instructions at decreasing prices). The price is determined by the AOT in the corresponding Energy bid.
4) Reverse service quality, i.e., SE, RR, NS, and SR.
5) RIE.

3.10. Special Resources

3.10.1. Participating Load

Participating load, i.e., load certified to provide IE services, can only supply NS or RR. There is no maximum ramp rate in association with participating load. No ramp rate can be bid for NS and the ramp rate bid for RR is ignored. Therefore, participating load responds to dispatch instructions immediately (i.e., with infinite ramp rate) after any relevant time delay. However, the schedule change ramp for ISO metered load is still given by (3).

3.10.2. Inter-tie Imports and Exports

The maximum and schedule-change ramp rates do not apply to imports and exports. Currently, exports can only provide SE. IE calculation from inter-tie dispatch is not based on ADS data or bid ramp rates, but on negotiated timestamps and ramp rates by Control Area operators. IE calculation is based on *block energy accounting*, at the effective time of the control area ramp i.e., infinite ramp rate.

4. ALGORITHM

The following flowchart illustrates the algorithm for calculating IE.

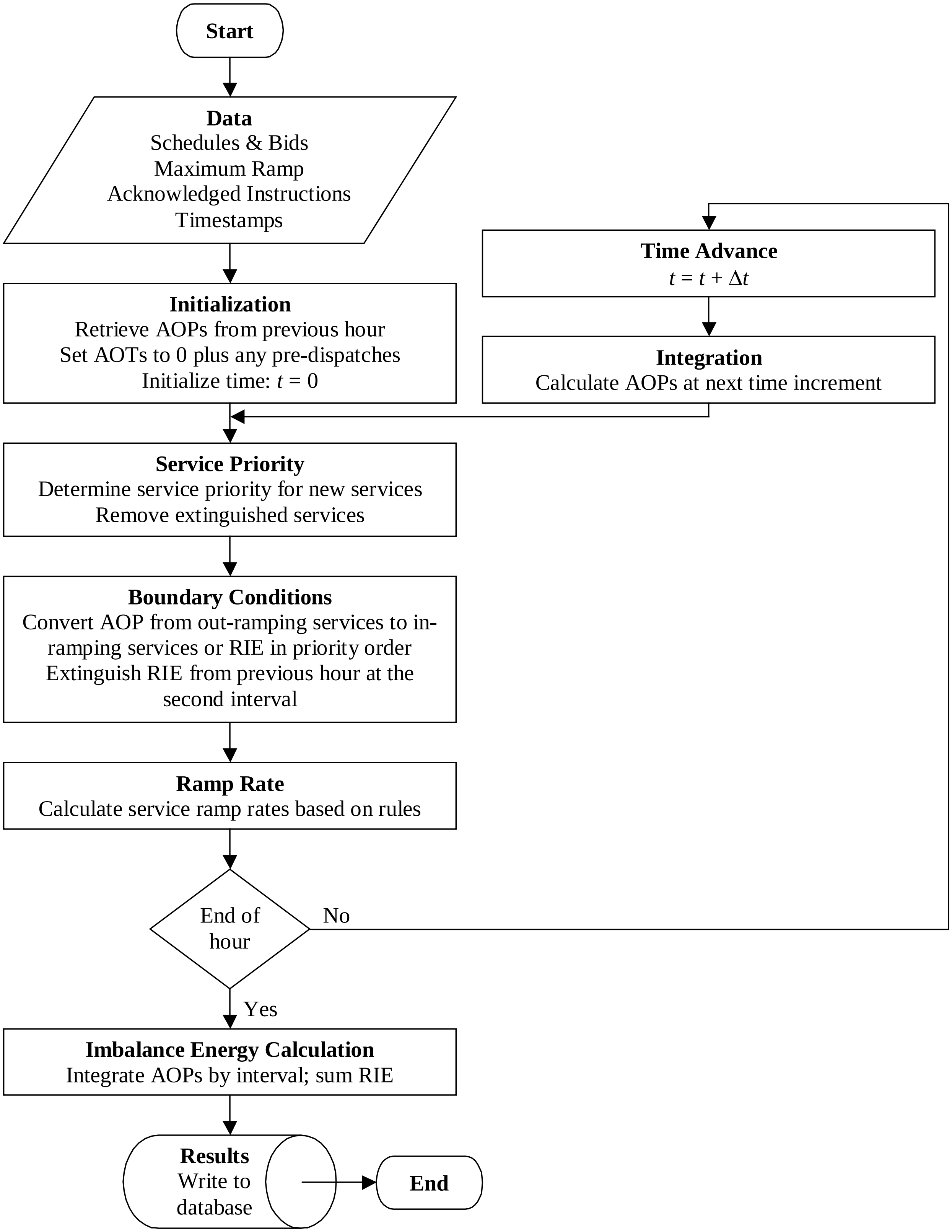


Figure 2. *IE Calculation Algorithm*

5. EXAMPLES

The examples in this section are for a 300MW unit with a 12MW/min maximum ramp rate. In all figures, the following legend applies:

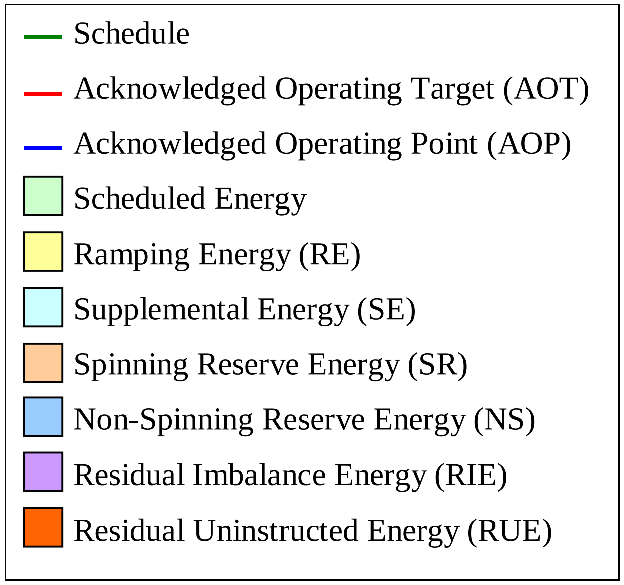
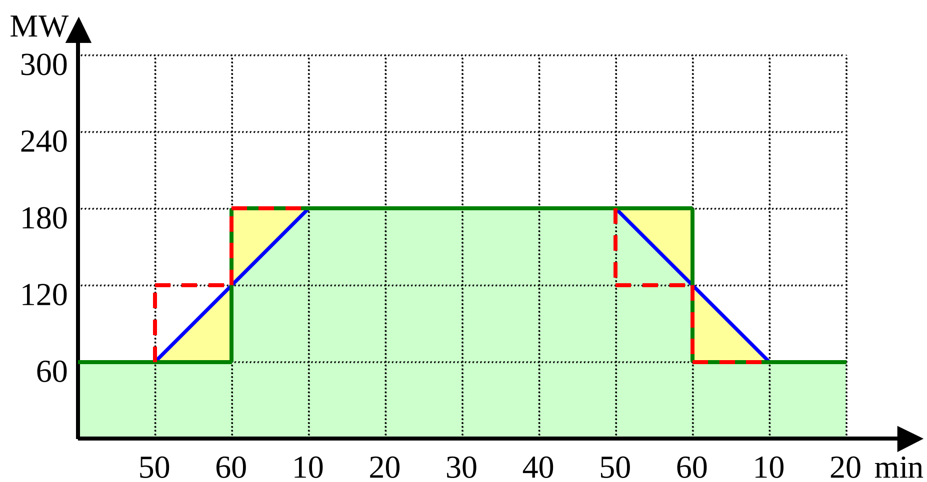


Figure 3. *Legend*

The AOT is shown dashed if it is due to implicit dispatch instructions.

5.1. Ramping Energy

Figure 4 shows the RE for hourly schedule changes. The RE is given by (2) and is constant irrespective of any other compounding services.

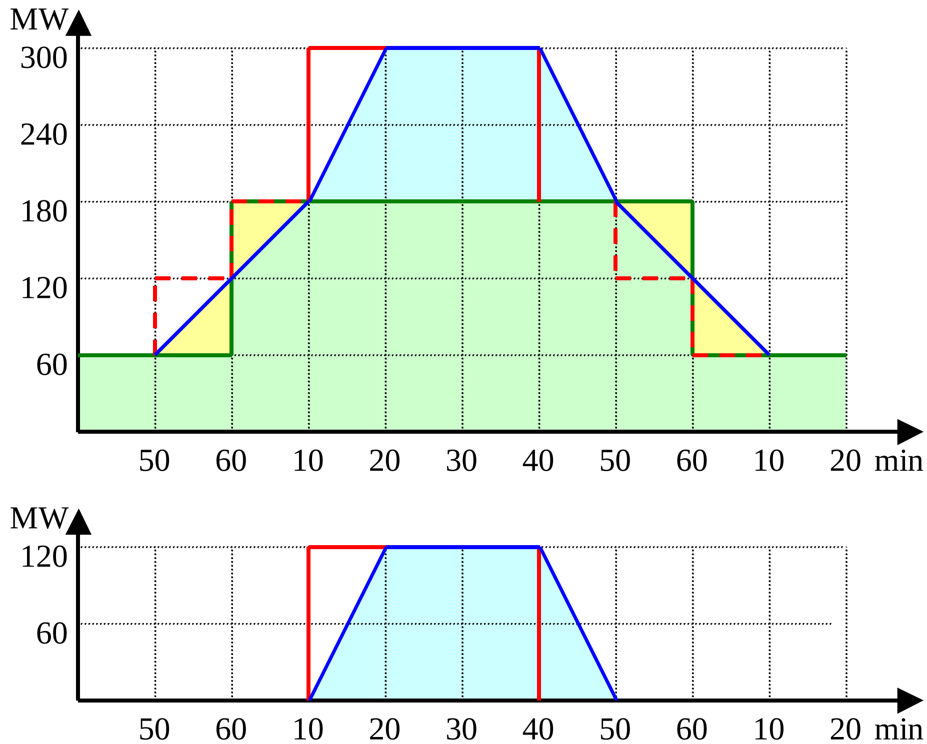


Interval	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
RE	0	5	–5	0	0	0	0	–5	5	0

Figure 4. *Ramping Energy*

5.2. Interval Imbalance Energy Without Overlap

Assume that the unit has bid 60MW SE at $10/MWh and another 60MW SE at $20/MWh with a ramp rate of 12MW/min. Figure 5 shows the SE for calling 120MW SE on at 10′ and 120MW SE off at 40′.

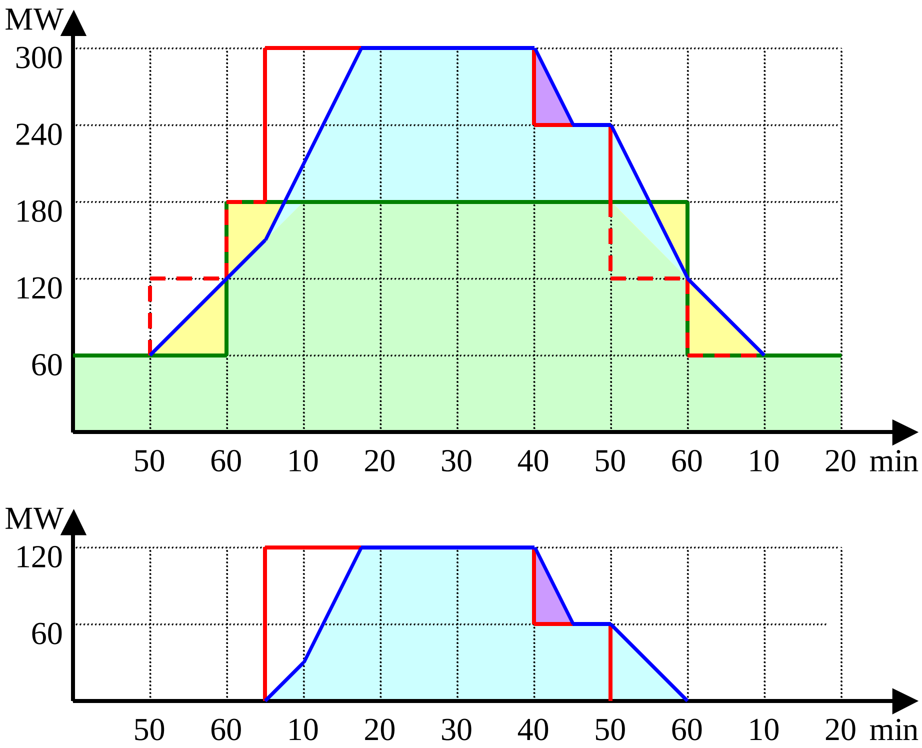


Interval	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
RE	0	5	–5	0	0	0	0	–5	5	0
SE	0	0	0	10	20	20	10	0	0	0

Figure 5. *Interval Imbalance Energy without overlap*

5.3. Interval Imbalance Energy With Overlap

Changing the previous example, Figure 6 shows the SE for calling 120MW SE on at 5′, 60MW SE off at 40′, and 60MW SE off at 50′. SE overlaps with RE in intervals 1 and 6. Calling off the higher priced SE block at the end of the 4th interval converts SE from that block to RIE in the 5th interval.

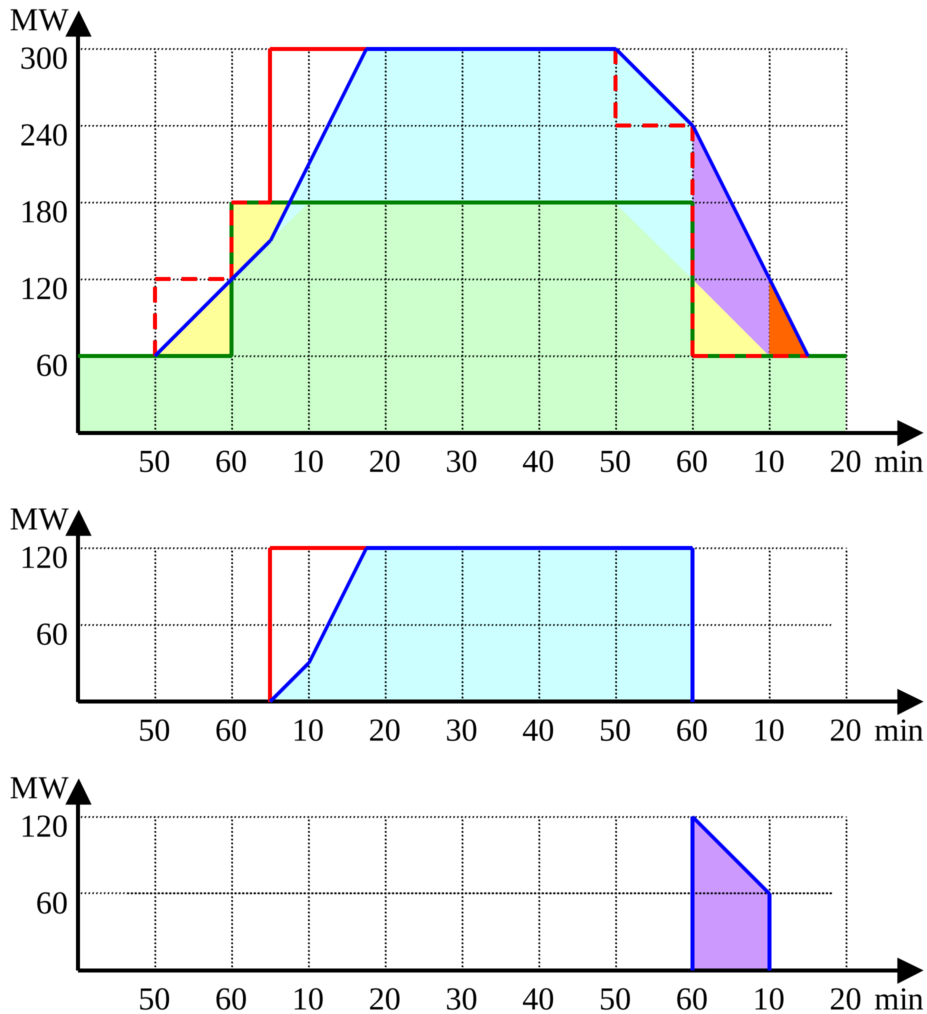


Interval	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
RE	0	5	–5	0	0	0	0	–5	5	0
SE	0	0	1.25	14.375	20	20	10	5	0	0
RIE	0	0	0	0	0	0	2.5	0	0	0

Figure 6. *Interval Imbalance Energy with overlap*

5.4. Residual Imbalance Energy

Changing the previous example, Figure 7 shows the SE for calling 120MW SE on at 5′ and expiring at 60′. SE overlaps with RE in intervals 1 and 6. SE is converted to RIE in the next hour.

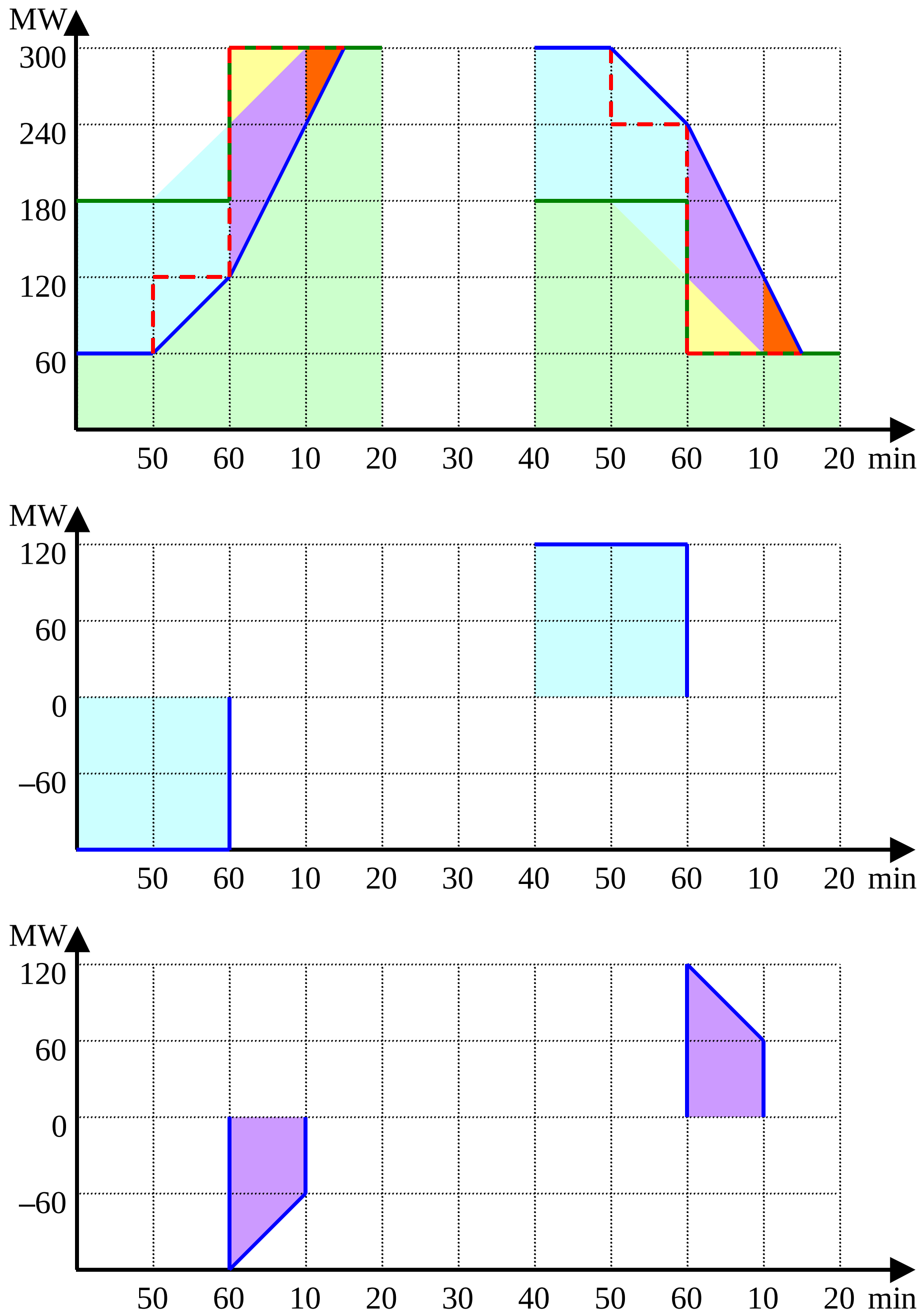


Interval	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
RE	0	5	–5	0	0	0	0	–5	5	0
SE	0	0	1.25	14.375	20	20	20	20	0	0
RIE	0	0	0	0	0	0	0	0	15	0

Figure 7. *Residual Imbalance Energy*

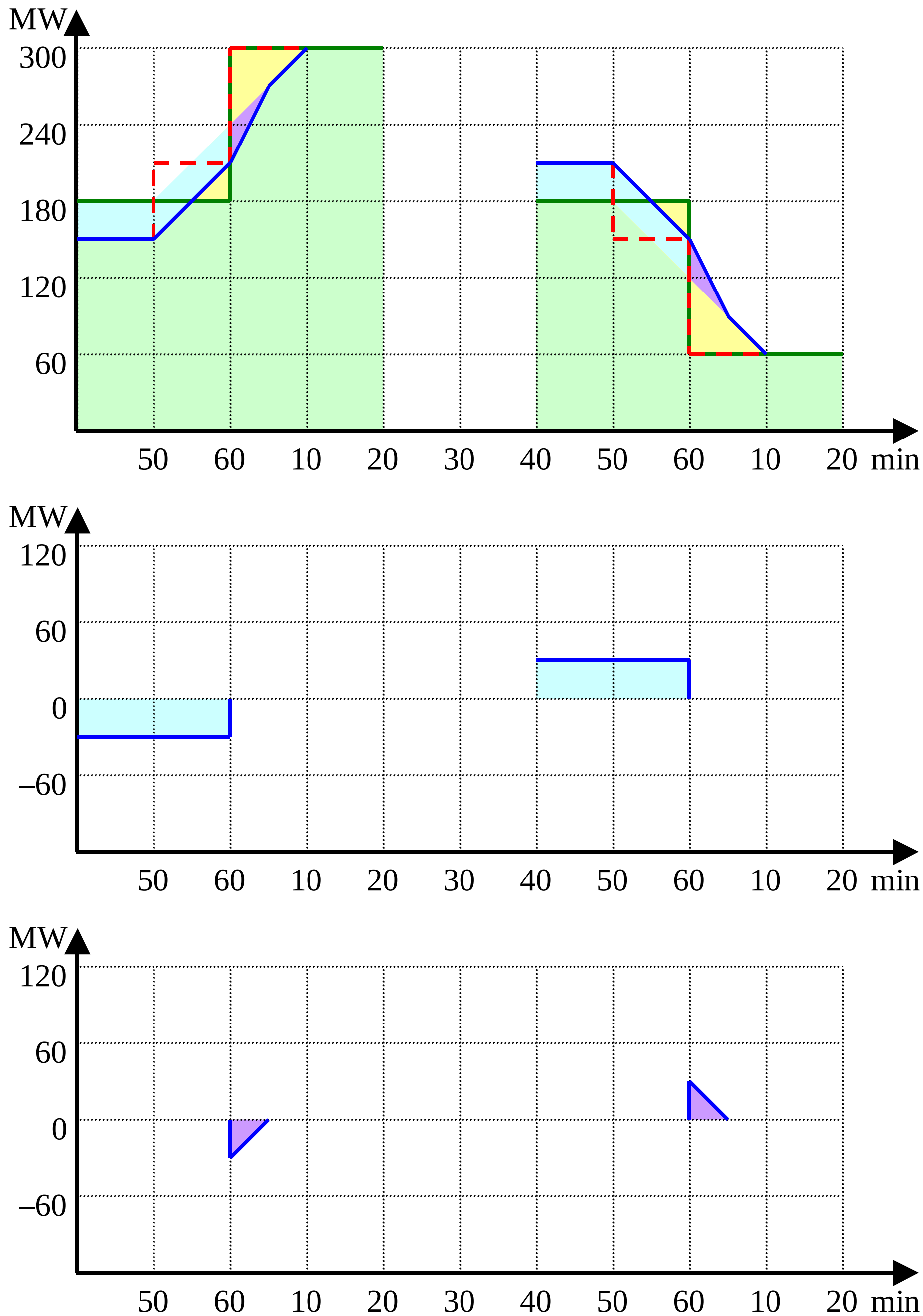
5.5. Hourly Transitions

Assume that the unit has bid up to ±300MW SE with a ramp rate of 12MW/min. The following figures show the RIE in the five possible hourly transition cases. The ramp rate for the RIE is given by (9), subject to boundary conditions (as shown in Cases 4 and 5).



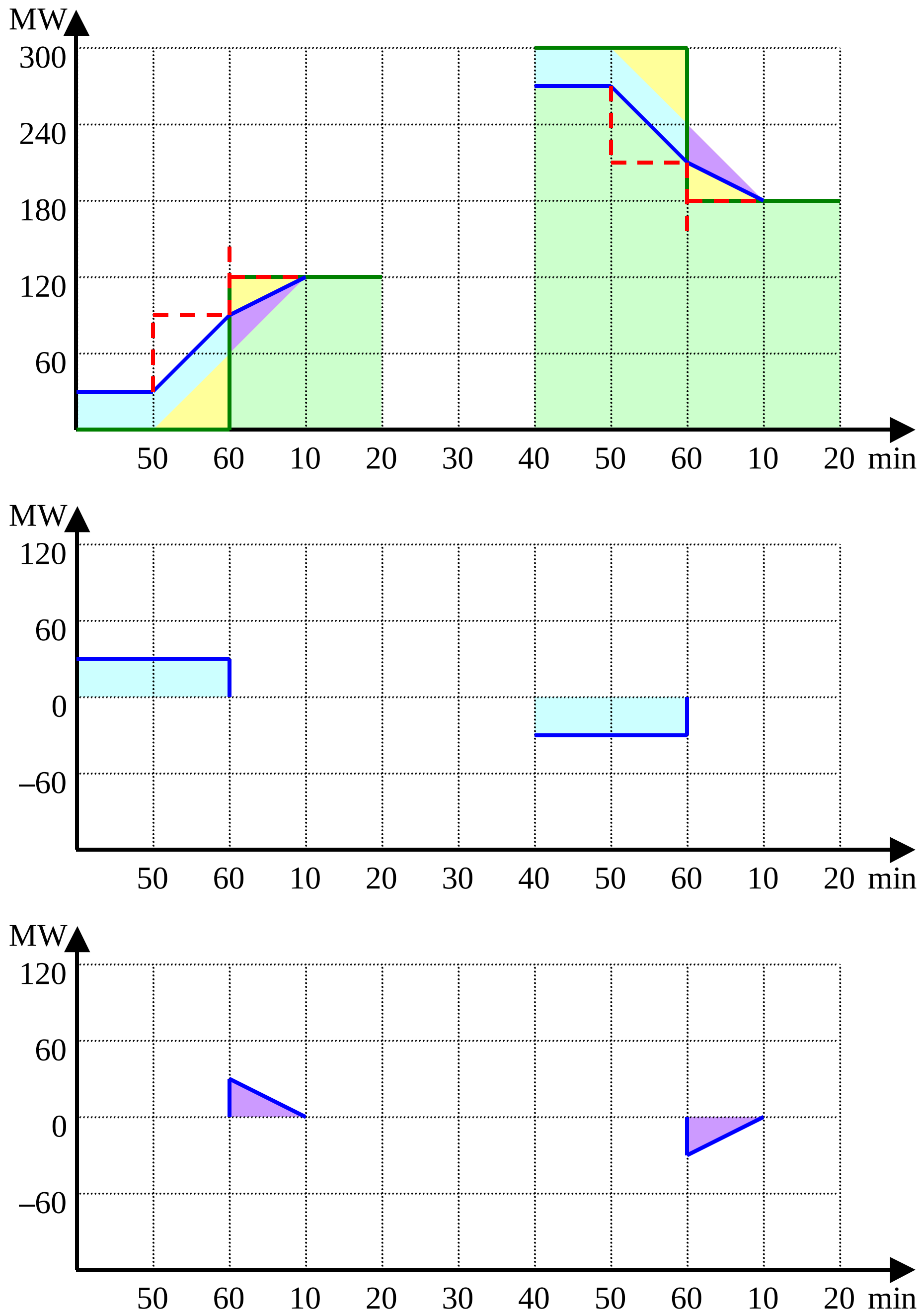
Interval	5	6	1	2	3	4	5	6	1	2
RE	0	5	–5	0	0	0	0	–5	5	0
SE	–20	–20	0	0			20	20	0	0
RIE	0	0	–15	0			0	0	15	0

Figure 8. *Hourly transition, Case 1*



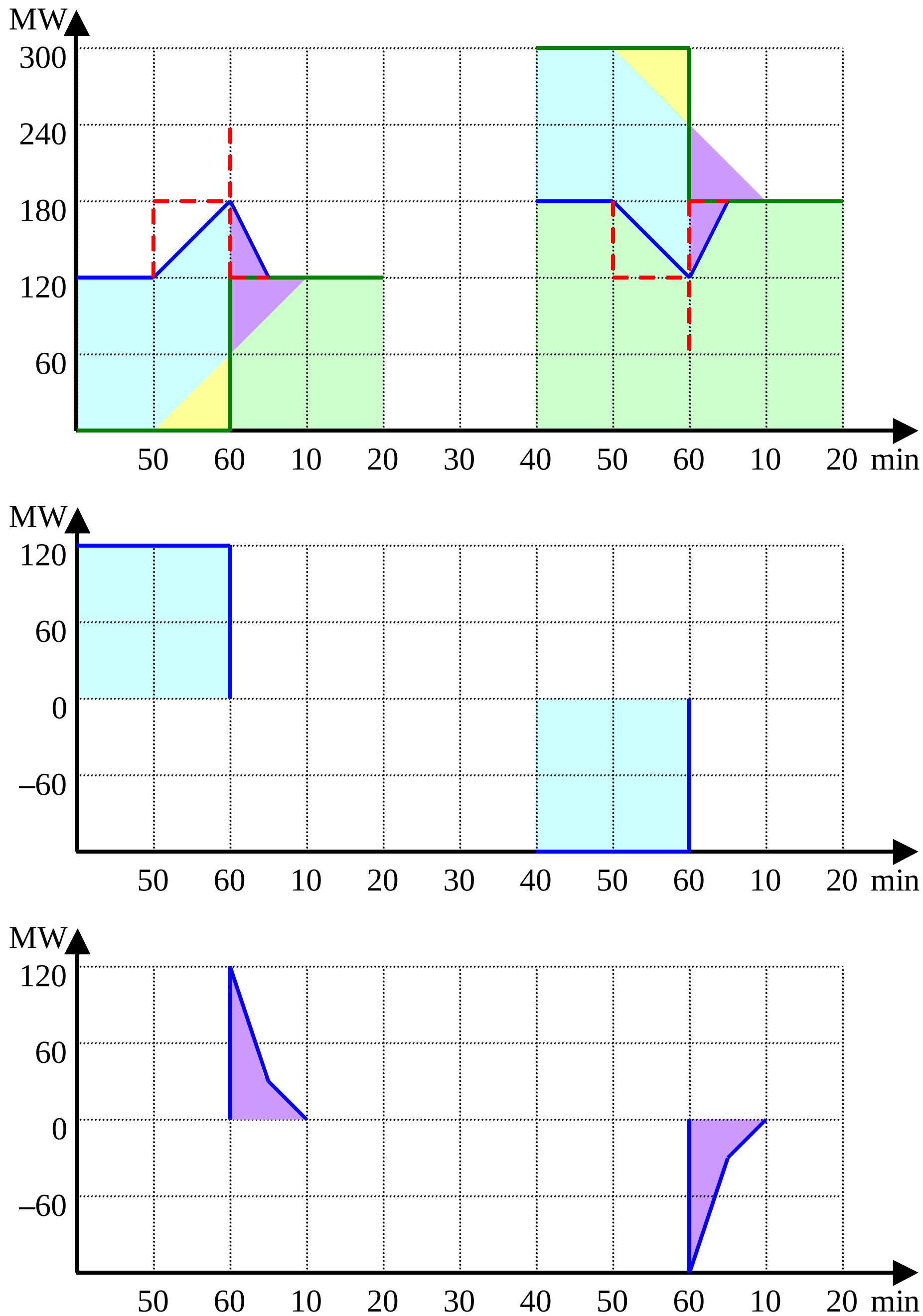
Interval	5	6	1	2	3	4	5	6	1	2
RE	0	5	–5	0	0	0	0	–5	5	0
SE	–5	–5	0	0			5	5	0	0
RIE	0	0	–1.25	0			0	0	1.25	0

Figure 9. *Hourly transition, Case 2*



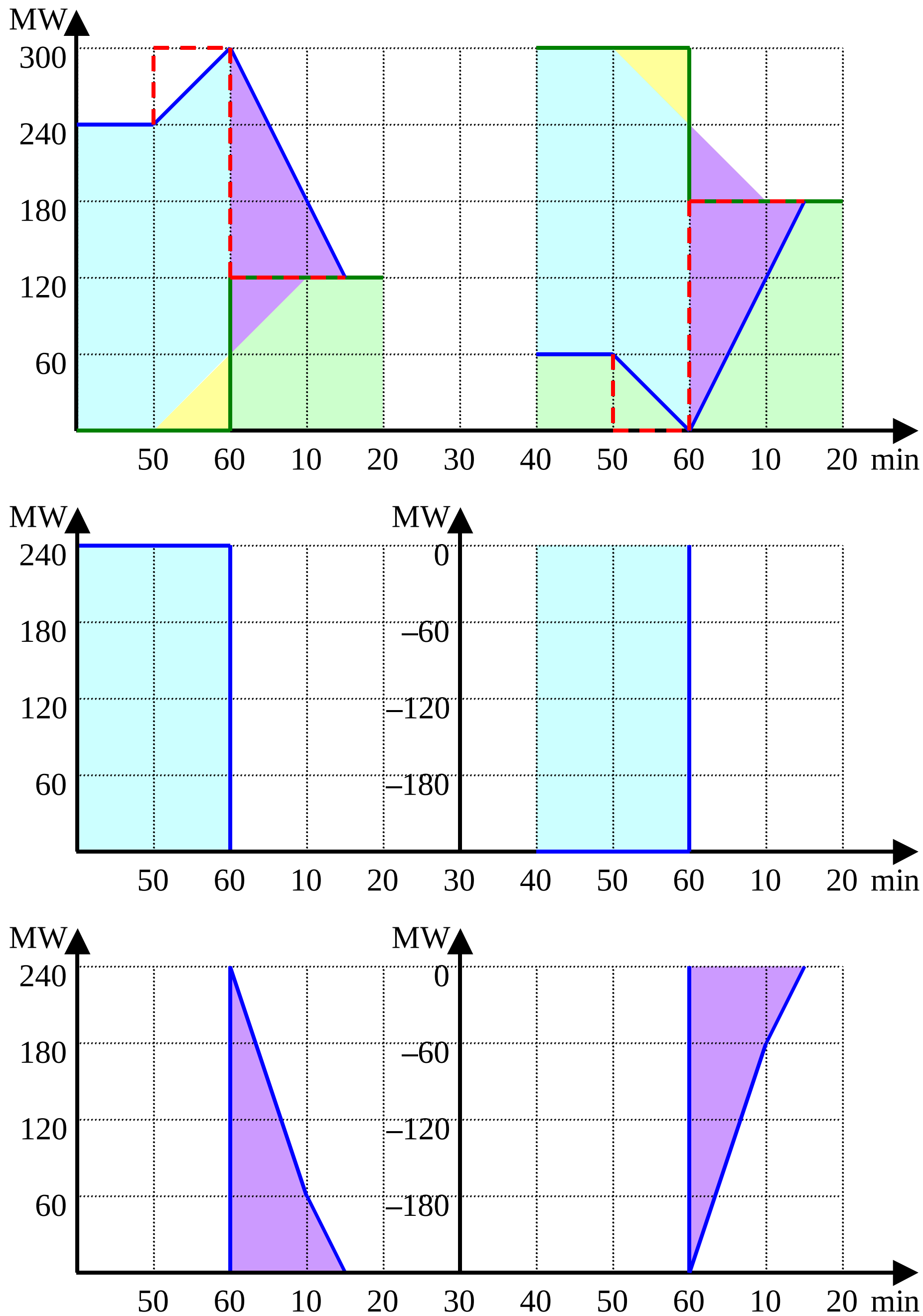
Interval	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
RE	0	5	–5	0	0	0	0	–5	5	0
SE	5	5	0	0			–5	–5	0	0
RIE	0	0	2.5	0			0	0	–2.5	0

Figure 10. *Hourly transition, Case 3*



Interval	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
RE	0	5	–5	0	0	0	0	–5	5	0
SE	20	20	0	0			–20	–20	0	0
RIE	0	0	7.5	0			0	0	–7.5	0

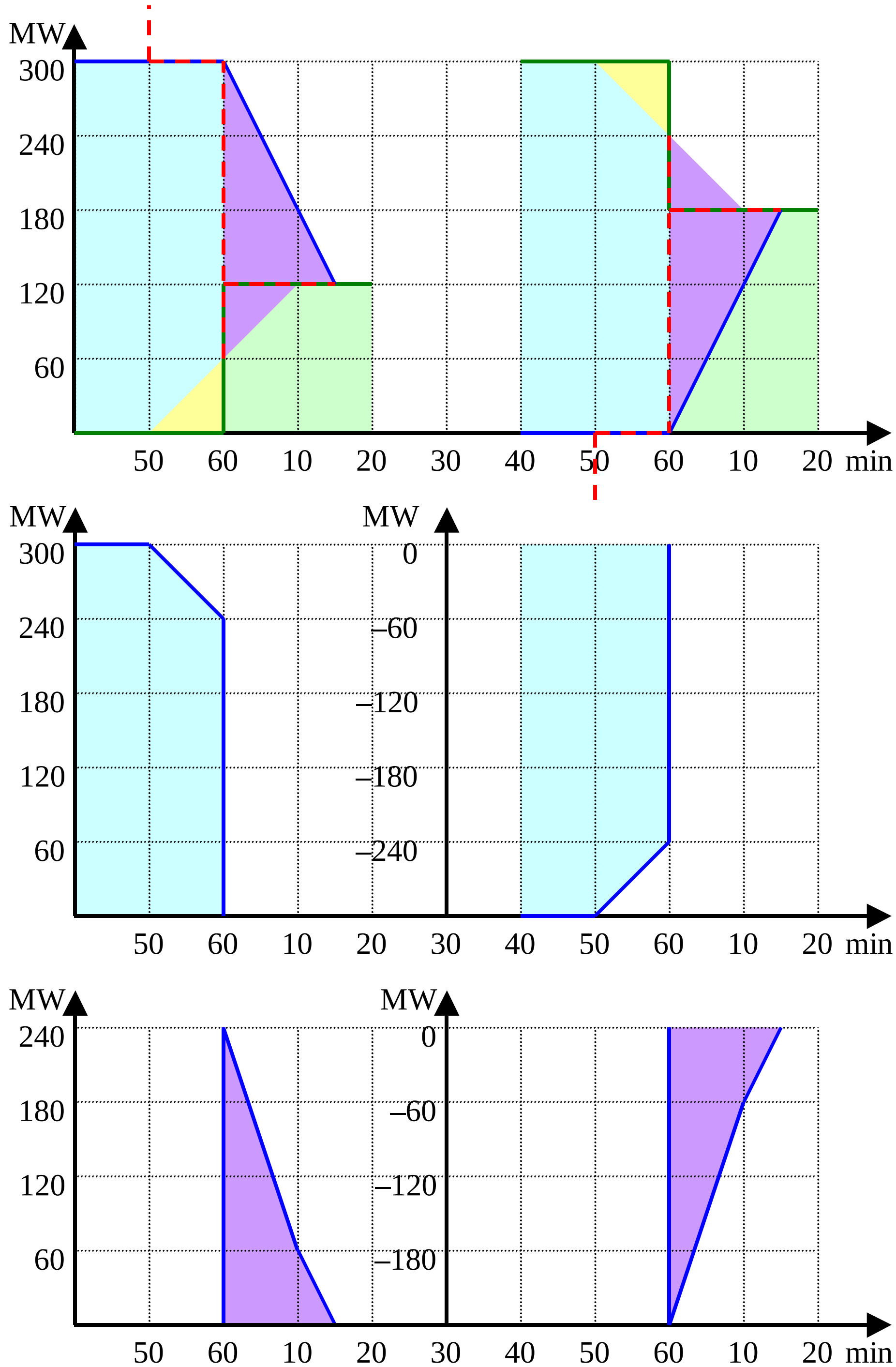
Figure 11. *Hourly transition, Case 4*



Interval	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
RE	0	5	–5	0	0	0	0	–5	5	0
SE	40	40	0	0			–40	–40	0	0
RIE	0	0	25	2.5			0	0	–25	–2.5

Figure 12. *Hourly transition, Case 5*

shows a variation of Case 5 where the IIE is reduced in the 5th interval (It is partially converted to RE) due to resource capacity limits.



Interval	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
RE	0	5	–5	0	0	0	0	–5	5	0
SE	50	45	0	0			–50	–45	0	0
RIE	0	0	25	2.5			0	0	–25	–2.5

Figure 13. *Hourly transition, Case 5 with binding resource limit*