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# Improved cost-benefit analysis for reliable long-term transmission planning

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***Abstract*—The aim of this paper is to incorporate reliability aspects in the transmission planning process presented in previous work. The decision maker has to consider many different aspects during the definition of transmission planning strategy, that sometimes might be contradicting. In the whole planning framework the decision is made by combining economic, environmental, and security of supply criteria in a single pseudo-dynamic algorithm. However, here only the part of security of supply is analyzed. After a sensitivity analysis for identification of critical/important transmission lines, a contingency analysis is performed and the probability of expected unserved energy is calculated together with the costs of expected unserved energy as an indicator. It is also shown that the amount of expected unserved energy is decreasing when additional transmission capacity is added to the connected lines of an unbalanced node. However, this may not be enough to reach zero unserved energy due to limitations of other transmission lines. After all, transmission network reinforcements can be evaluated based on benefits in avoided environmental costs, avoided congestion costs and avoided unserved energy costs in order to provide sufficient information to the decision maker.**

***Index Terms*—Future electric power systems, transmission planning, reliability, cost-benefit analysis.**

## I. INTRODUCTION

In the present dynamically changing power systems environment many uncertainties appear. Thus, the transmission planning becomes more and more an exercise where many aspects have to be considered, as shown in Fig. 1

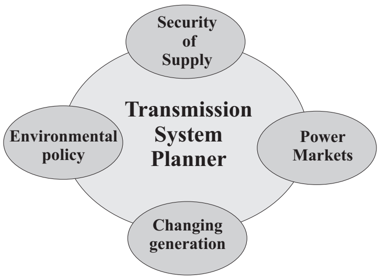

Fig. 1. Planning framework

So far, the transmission network planning process has been identified as multi-criteria, multi-objective, multi-stage process, [2],[3], while no environmental aspects have been considered and only few information is given specifically for the European interconnected system and its characteristics as a whole. In previous work [7] the generation and transmission models have been combined in a cost-benefit analysis in order to evaluate potential transmission expansion plans in the European interconnected system. Avoided environmental costs (AEC) and avoided congestion costs (ACC) due to additional transmission capacity had been compared to transmission lines investment costs. However, in this work a detailed description of the identification of proposed candidate lines, together with an indicator for system reliability analysis, was missing.

Furthermore in the system adequacy studies of ENTSO-E, the capacity exchanges between countries is considered as infinite, which is not so realistic [4].

This paper contributes in the characterization of the European electricity network and its long-term reliability analysis considering transmission capacity limits and voltage angle limits. After the identification of critical interconnected lines the probability of unserved energy on each node, if any, is calculated for cases with and without transmission network reinforcement. The whole study is based on an aggregated copper-plate model of EU-20, that was developed in order to perform economic studies in the system of continental Europe.

## II. TRANSMISSION PLANNING PROCESS

The transmission planning process consists of 5 steps presented in Fig. 2. The final decision and the evaluation of transmission investment plans is not in the scope of this paper.

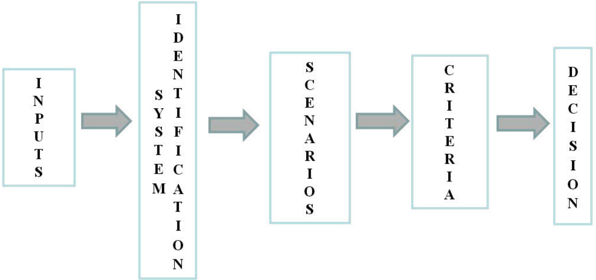

Fig. 2. Detailed planning process

During the planning process the inputs such as generation, consumption data and marginal production costs are the most uncertain [5]. Other inputs, e.g. transmission lines data and environmental costs are considered as known. The variability of the inputs influences strongly the selection of transmission

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investment scenarios, the output indicators and therefore the final decision. Hence, a sensitivity analysis is needed in order to characterize the system. The criteria used are indicators that provide information on the impact of the selected scenarios on societal, environmental, economic and reliability factors. Societal or economic indicators are for instance change in social welfare, in nodal prices, in congestion costs and in operational costs. Environmental indicators show the change in production of conventional power plants or the increase of green power production due to the additional transmission network capacity. Reliability indicators provide information of change in unserved energy or in value of lost load, that can also be used in the long-term.

The three steps of the reliability evaluation of transmission network reinforcement are the following:

1) Identification of important interconnections or group of interconnections based on probability of congestion in different load and generation scenarios.
2) Calculation of probability of unserved energy for each node when some important lines or groups fail.
3) Calculation of probability of unserved energy again, this time considering transmission capacity reinforcement.

## III. UNSERVED ENERGY CALCULATION

The optimization is based on DC-OPF for nodal price calculation [6], subject to nodal equality constraints, generation capability limits, transmission capacity limits and voltage angle limits. The reliability indicator used here is the unserved energy when an outage of an interconnection or group of interconnections occurs. The modelling approach of unserved energy is described below.

In order to avoid convergence problems, the unserved energy has been modelled as an additional in-feed source on each node with a very high cost assigned to it. Thus, it is a kind of emergency capacity that is used when the node is not able to cover it is own demand in case of outage.

The DC-OPF formulation is the following:

$$min\{\sum_{i=1}^{n} MPC_i\} \Rightarrow min\{\sum_{i=1}^{n}(\Pi_i) * P_i\} \tag{1}$$

s.t.

| equalities | inequalities |
|---|---|
| $P_i - L_i - \sum Pf_{ij} = 0$<br>$L_i = inelastic$ | $P_i, L_i > 0$<br>$P_{i_{min}} \leq P_i \leq P_{i_{max}}$<br>$-TCL_{ij_{min}} \leq Pf_{ij} \leq TCL_{ij_{max}}$<br>$\lvert\theta_i\rvert \leq \theta_{max}$ |

where

| | |
|---|---|
| n | number of nodes |
| $MPC_i$ | marginal production cost for a node i (€/MWh) |
| $\Pi_i$ | marginal price for a specific level of injected power (€/MWh) |
| $P_i$ | aggregated injected power at node i, including unserved energy (MW) |
| $L_i$ | demanded power at node i (MW) |
| $TCL_{ij}$ | the transmission capacity limit from node i to node j, equal to the net transfer capacity (MW) |
| $Pf_{ij}$ | power exchanges from node i to node j (MW) |
| $\theta_i$ | voltage angle of node i |

## IV. COST-BENEFIT ANALYSIS

In this paper a cost-benefit analysis is used that considers environmental, economic and technical benefits. The analysis helps along with the selection of a reinforcement $k$ in the transmission network. The benefits from a proposed transmission project consist of a societal, a market based and a reliability element like in eq. 2. The first element is assigned to less $CO_2$ emissions due to less utilization of conventional power plants, the second to the reduction of congestion costs and the third one to the reduction of unserved energy on some nodes of the network when an incident occurs. A similar approach has been used in [7], however without the consideration of environmental and market based aspects.

$$benefits_k = (AEC_k + ACC_k + AUEC_k) \tag{2}$$

a) Avoided environmental costs (AEC): when new capacity in generation and transmission is available, the dispatch of the power plants changes as well, which means that the output power of some conventional power plants will change consequently. In order to calculate the environmental benefits derived from a proposed project, the difference of the generation output with and without the new transmission capacity has been used as shown in eq. 3:

$$AEC_k = \sum_{i=1}^{nodes} \Delta Q_i * EC_i \tag{3}$$

where

| | |
|---|---|
| $EC_i$ | is the external cost per MWh associated with each type of production fuel. In this paper only $CO_2$ costs are taken into account, but other costs can also be included. |

b) Avoided congestion costs (ACC): This cost represents the congestion costs that could be avoided by the use of the new transmission line. The congestion costs are calculated as the product of the nodal price difference between two nodes $i$ and $j$, and the amount of power transfer between these two nodes $Pf_{ij}$. This method is widely used for congestion management in pool markets, e.g. PJM [8]. The avoided congestion cost is calculated for each candidate lines for all the years considered, eq. 4.

$$ACC_k = \sum_{i,j=1}^{nodes} (\Pi_i - \Pi_j) * Pf_{ij} \tag{4}$$

c) Avoided unserved energy costs (AUEC): network transmission reinforcement allows more power be transmitted to critical nodes when a transmission line is not available. Therefore, less energy remains unserved and the social costs decrease. Some typical values of social cost of unserved energy are provided in [9].

Finally, the total benefits of the project are compared to the costs and a profitability indicator of the whole project is provided to the desicion maker. However, due to the complexity of the problem and the consideration of contradicting interests in the analysis, the final decision may differs from the most economical solution according to the predefined preferences.

## V. MODEL DESCRIPTION

In this section the studied model of the European model is described. An aggregated European model has been created appropriate for transmission network planning studies and examination of how the generation mix change interacts with it. Thus, not only investments in new generation technologies but also the constraints of the transmission network could be considered in the system. For the development of the model only publicly available data from ENTSO-E and former UCTE have been used.

The model consists of 20 nodes, that represent 20 countries of western and southeastern Europe. Each node is connected to another, only if an interconnection is existing. On every node 5 different production technologies are assigned, e.g. nuclear, hydro, gas, coal and renewables. Generation capacities are aggregated for the whole country according to the maximal installed capacity reported from UCTE in 2008. The same for the load levels and the interconnection capacities, that where assumed to be equal to the net transfer capacities (NTC) as aggregated transfer capabilities. Other line characteristics, e.g. line reactance, were based on typical values and on an impedance calculator provided by Powerworld software in which the model is implemented.

in Fig. 3, the different prices zones and some typical congested lines are depicted after the calculation of a standard DC optimal power flow. With red color the most expensive price zone is indicated, while with light blue is the cheapest. The yellow - green is the middle range area. From the picture is obvious that Italy, the most expensive node in the system is with need of imports. In general the power flows from west to east and north to south for the selected snapshot of the system.

## VI. SYSTEM CHARACTERISATION & IDENTIFICATION OF CRITICAL PATHS

In this section, the model described previously is characterised and typical critical paths are identified according to the probability of congestion between nodes. As the model does not provide very detailed information about the internal transmission network within a country, critical components are supposed to be only interconnection lines. A sensitivity analysis is used in order to identify the critical paths or geographical regions in the network. The sensitivity analysis is based on scenarios for variable load of ± 5% for the 20 countries included in the model. The load condition of winter peak load of the 3rd Wednesday, January 2009 is taken as starting point. Besides the demand variation, different generation conditions are also taken into account. Therefore, an amount of 306 cases is generated in order to calculate the probability of overloading on the interconnections. Overloading here means loading more than 80% of the total net transfer capacity of a line. The results of overloading probability are presented in Fig. 4.

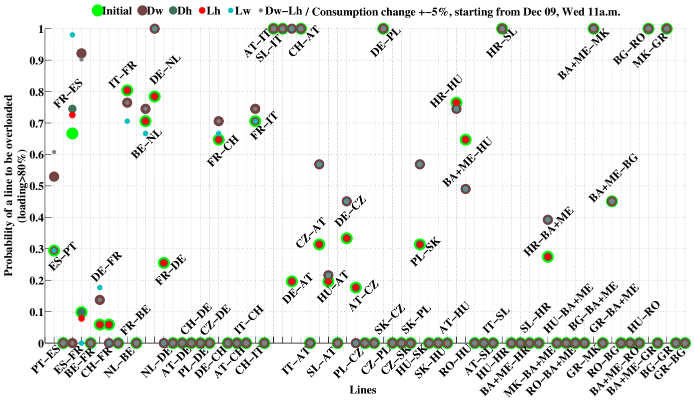

Fig. 4. Probability of lines to be loaded over 80%

The different generation conditions that have been studied are the following:

- Ititial set-up 3rd Wed. 19:00pm Jan.2009 (initial).
- Dry year, half hydro power availability for CH, AT, ES, (low hydro, lh).
- Low wind, half wind power availability for DE, ES, NL, IT, (low wind, lw).
- Double wind, double wind power availability for DE, ES, NL, IT, (double wind, dw).
- Double hydro power availability for CH, AT, ES, (double hydro, dh).
- Double wind and low hydro power availability for the previous mentioned countries, (Double wind-low hydro, dw-lh).

From the sensitivity analysis derives that some lines are permanently congested, no matter what the load level or the generation set-up is. These lines are between AT-IT, SL-IT, CH-AT, HR-SL, BG-RO and MK-GR. Other lines are more sensitive to load or generation changes, however still with a high probability of loading over 80%. Lines with a probability lower than 0.7 are not considered in the reliability analysis.

The reliable available capacity when the unavailable capacity and the reserved capacity for system services are subtracted is presented in Fig. 5. This margin represents the maximum capacity that can be used at a certain moment in order to cover the demand without consideration of any imports-exports. It is obvious that for the initial set-up of the system the nodes are able to operate under isolated conditions neglecting any demand growth. Nevertheless, in case of interconnection outage for any reason, and simultaneous demand growth or different generation availability, some of the nodes are going to remain unbalanced and a certain amount of demand is considered as unserved.

## VII. CONTINGENCY ANALYSIS

For the contingency analysis, the unserved energy probability of a node is calculated, when only one interconnection is on outage. As the interconnections represent aggregated transfer capacities, two cases for reduced transfer capability

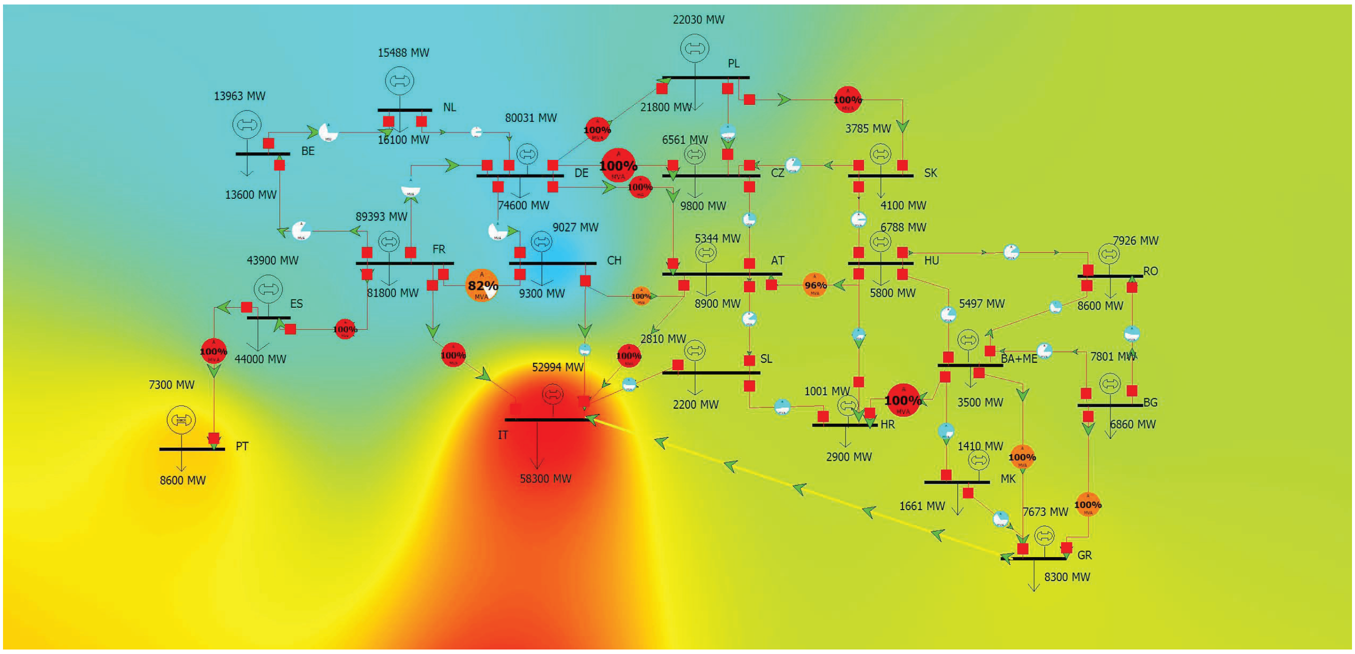

Fig. 3. European aggregated model, Winter peak load.

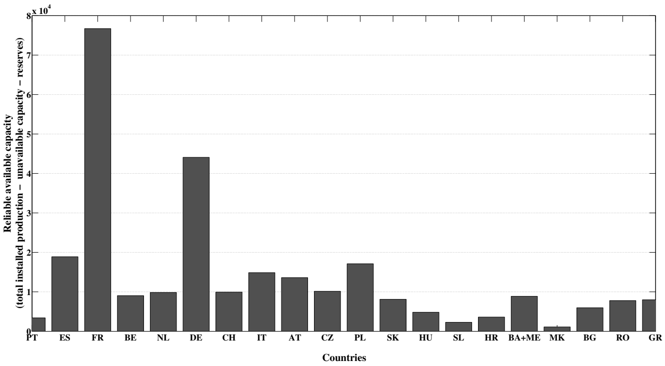

Fig. 5. Reliable available capacity when the unavailable capacity and the reserved capacity for system services are subtracted

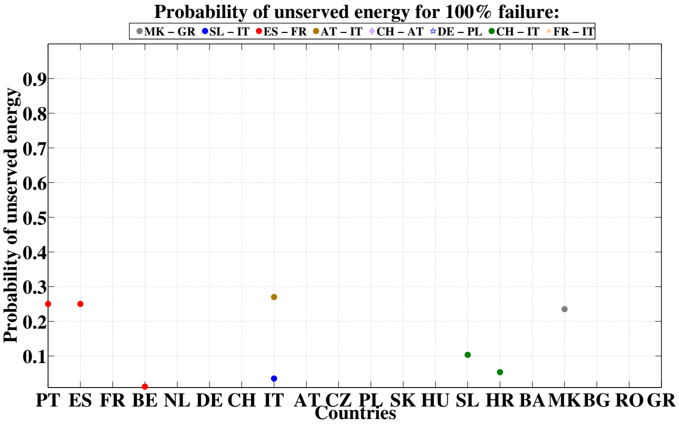

Fig. 6. Probability of unserved energy

have been considered. One for 100% and one for 50% of the whole transmission capacity. This means that most probably only 1 or 2 lines are out of order. For failures less than 50% all nodes are able to cover their own load, while with increasing failure level the effects are closer to the results analyzed below. Each time an interconnection fails a sensitivity analysis for the aforementioned generation scenarios is performed. This time the demand varies randomly on a normal distribution picking up 100 samples for each node. Using this controlled randomize selection of demand an average increase of 5-6% of the total system load is achieved. Only the following lines are considered in this contingency analysis: AT-IT, SL-IT, CH-AT, CH - IT, FR - IT, DE - PL, ES - FR and MK-GR.

The results of probability of a node to be unbalanced are presented in Fig. 6 referring to 100% failure of a line in the model. Besides the observation that Italy might be unbalanced with a probability of 5% when the line SL -IT fails and with 28% when the line AT -IT fails, there are two other important results. The first refers to the failure between Spain and France. When this capacity is unavailable the nodes of Portugal and Spain remain unserved with the same probability of 25% and also Belgium with a very low percentage. This is explained from the high cheap production capacity of France that acts as an important exporter. When this line is trips an island of Spain and Portugal is created that cannot cover its own demand with a quite high probability. The second interesting result refers to the line failure between Switzerland and Italy. In this case Italy is able to cover the local load, however Slovenia is weakly interconnected to the neighbors and cannot import the needed power, as well as Croatia. The remaining available capacity on these nodes are also not enough and thus Slovenia and Croatia remain unbalanced with a probability of 10% and 5% respectively.

In order to calculate the total unserved energy costs, it's important to know how much is the unserved energy and how much does a MWh of unserved energy cost. In different studies, different numbers for estimated unserved energy costs appear distributed in residential industrial and mixed residential areas, e.g. in [10]. The unserved energy price turns to be very high compared to the marginal production prices, due to many influenced parties and negative effects. For this case study a cost of 3000€/MWh has been assumed, which seems to be an optimistic estimation. In Table I below the unserved energy and the resulted costs for occurrence event are presented:

TABLE I
AMOUNT OF UNSERVED ENERGY

| Event | Unserved Node | Costs (€/h) |
|---|---|---|
| ES - FR | PT | $0.631 \cdot 10^6$ |
| | ES | $1.525 \cdot 10^6$ |
| | BE | $0.025 \cdot 10^6$ |
| SL - IT | IT | $2.746 \cdot 10^5$ |
| AT - IT | IT | $6.656 \cdot 10^5$ |
| CH - IT | SL | $0.3217 \cdot 10^3$ |
| | HR | $4.2075 \cdot 10^3$ |
| MK - GR | MK | $6.438 \cdot 10^4$ |

As aforementioned in section IV, network reinforcements may be from different aspects beneficial for the society and for the network itself. From the amount of calculated costs of unserved energy can be stated that the reduction of unserved energy is as an important indicator as the benefits from environmental costs reduction or congestion costs reduction.

## VIII. NETWORK REINFORCEMENTS

In this section an example of network reinforcement and its impact on unserved energy is examined. As an example here it is used the contingency scenario of the line between Italy and Austria, as it leads to the highest probability of unserved energy for Italy. A reinforcement is assumed to be made on the line between Switzerland and Italy with an initial capacity of 3890MW. The line capacity is then increased by 10% for several steps until a low amount of unserved energy is reached. Fig. 7 shows the relation between the amount of unserved energy and the additional transmission capacity.

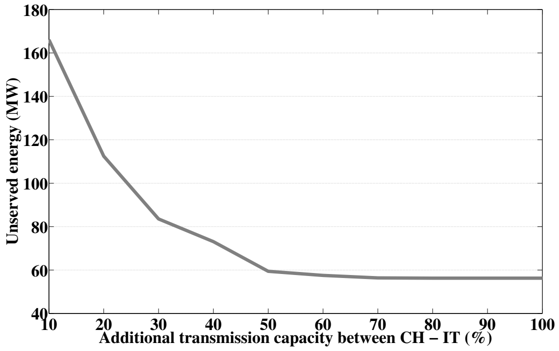

Fig. 7. Decrease of unserved energy in IT with the increase of transmission capacity for line reinforcement CH-IT

From the picture derives that the amount of reduction of unserved energy is not linearly dependent from the additional capacity of the line, which means the amount of reduced unserved energy is not equal to the amount of increased capacity of the line. It is additionally shown that no matter how big the transmission capacity of this line is, it is not enough to lead to zero unserved energy, due to transmission limitations of the neighboring lines. This observation could initiate combined reinforcements in meshed interconnected systems involving many control areas and TSOs.

The previously calculated amount of reduced unserved energy due to new available capacity at an interconnector could be used in the cost-benefit analysis as an additional benefit. Of course, the problem remains a problem of contradicting interests as the lowest amount of unserved energy refers to the highest transmission lines capacity, however the more the transmission capacity the higher the investment costs. Combining environmental, congestion and unserved energy benefits a wide scope of the impact of the transmission investment is provided that facilitates the final investment decision.

## IX. CONCLUSION

A completed transmission planning takes into consideration many aspects, that should build a clear picture of the impact of the investment on the whole system. This paper focuses on the impact of interconnection failures at critical areas on unserved energy performing a sensitivity analysis. Six generation mix scenarios have been considered combined with randomly chosen load variations on every node, in order to calculate congestion probabilities of lines and probabilities of unserved energy on the nodes. The contingency analysis has shown that the developed model is quite robust and only a little amount of demand remains unserved. However, due to high estimated costs of unserved energy, this indicator can be integrated in a cost - benefit analysis together with environmental and congestion benefits, when a transmission line is reinforced. Accordingly, transmission investment plans could be evaluated based on an improved cost-benefit analysis that takes into account societal, economic and reliability standards.

## APPENDIX A
## NODES AND COUNTRIES ABBREVIATIONS

TABLE II

| Node | abbr. | Country |
|---|---|---|
| 1 | PT | Portugal |
| 2 | ES | Spain |
| 3 | FR | France |
| 4 | BE | Belgium |
| 5 | NL | Netherlands |
| 6 | DE | Germany |
| 7 | CH | Switzerland |
| 8 | IT | Italy |
| 9 | AT | Austria |
| 10 | CZ | Czech Republic |
| 11 | PL | Poland |
| 12 | SK | Slovakia |
| 13 | HU | Hungary |
| 14 | SL | Slovenia |
| 15 | HR | Croatia |
| 16 | BA+ME | Bosnia / Serbia |
| 17 | MK | F.Y.R.O.M. |
| 18 | BG | Bulgaria |
| 19 | RO | Romania |
| 20 | GR | Greece |

## Appendix B
## Transmission Line Parameters

TABLE III

| From | To | Capacity (MW) | Reactance |
|---|---|---|---|
| 1 | 2 | 1300 | 34 |
| 2 | 3 | 1400 | 30 |
| 3 | 4 | 2200 | 22 |
| 3 | 8 | 995 | 36 |
| 3 | 6 | 2750 | 27 |
| 3 | 7 | 2300 | 35 |
| 4 | 5 | 2400 | 34 |
| 6 | 5 | 3000 | 27 |
| 6 | 11 | 1200 | 29 |
| 6 | 7 | 3200 | 22 |
| 6 | 10 | 2250 | 29 |
| 6 | 9 | 1800 | 36 |
| 10 | 11 | 1750 | 36 |
| 10 | 12 | 1000 | 55 |
| 10 | 9 | 650 | 36 |
| 11 | 12 | 550 | 32 |
| 7 | 9 | 600 | 36 |
| 7 | 8 | 1810 | 36 |
| 8 | 14 | 430 | 36 |
| 8 | 9 | 220 | 36 |
| 14 | 15 | 900 | 36 |
| 14 | 9 | 650 | 32 |
| 13 | 9 | 500 | 41.3 |
| 13 | 16 | 500 | 36 |
| 13 | 12 | 1500 | 38 |
| 13 | 15 | 400 | 36 |
| 13 | 19 | 800 | 29 |
| 15 | 16 | 700 | 28 |
| 16 | 19 | 500 | 29 |
| 16 | 17 | 250 | 33 |
| 16 | 18 | 500 | 28 |
| 16 | 20 | 30 | 29 |
| 18 | 19 | 750 | 22 |
| 20 | 17 | 70 | 36 |
| 20 | 18 | 500 | 30 |
| 20 | 8 | 500 | 46 |

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